OPTIMIZATION OF MACHINING PARAMETERS IN A TURNING OPERATION OF AUSTENITIC STAINLESS STEEL TO MINIMIZE SURFACE ROUGHNESS AND TOOL WEAR

A Thesis submitted in partial fulfillment of the requirements for the degree of

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By

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CERTIFICATE

This is to certify that the thesis entitled "**Optimization of machining parameters in a turning operation of austenitic stainless steel to minimize surface roughness and tool wear**", submitted by **Yashaswi Agrawalla** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Mechanical Engineering** during session 2013-2014 at National Institute of Technology, Rourkela is an authentic work carried out under my supervision and guidance. The candidate has fulfilled all the prescribed requirements.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other university/ institute for award of any Degree or Diploma. In my opinion, the thesis is of the standard required for the award of a bachelor of technology degree in Mechanical Engineering.

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ABSTRACT

The present work concerned an experimental study of turning on Austenitic Stainless steel of grade AISI 202 by a TiAlN coated carbide insert tool. The primary objective of the ensuing study was to use the Response Surface Methodology in order to determine the effect of machining parameters viz. cutting speed, feed, and depth of cut, on the surface roughness of the machined material and the wear of the tool. The objective was to find the optimum machining parameters so as to minimize the surface roughness and tool wear for the selected tool and work materials in the chosen domain of the experiment. The experiment was conducted in an experiment matrix of 20 runs designed using a full-factorial Central Composite Design (CCD). Surface Roughness was measured using a Talysurf and tool wear with the help of a Toolmaker's microscope. The data was compiled into MINITAB ® 17 for analysis. The relationship between the machining parameters and the response variables (surface roughness and tool wear) were modelled and analysed using the Response Surface Methodology (RSM). Analysis of Variance (ANOVA) was used to investigate the significance of these parameters on the response variables, and to determine a regression equation for the response variables with the machining parameters as the independent variables, with the help of a quadratic model. Main effects and interaction plots from the ANOVA were obtained and studied along with contour and 3-D surface plots. The quadratic models were found to be significant with a p-value of 0.033 and 0.049. Results showed that feed is the most significant factor affecting the surface roughness, closely followed by cutting speed and depth of cut, while the only significant factor affecting the tool wear was found to be the depth of cut. The top three optimum settings for carrying out the machining were obtained from Response Surface Optimizer and are shown in the results section.

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Chapter 1 INTRODUCTION

1.1 INTRODUCTION AND STATE OF ART

The turning operation is a basic metal machining operation that is used widely in industries dealing with metal cutting [1]. The selection of machining parameters for a turning operation is a very important task in order to accomplish high performance [2]. By high performance, we mean good machinability, better surface finish, lesser rate of tool wear, higher material removal rate, faster rate of production etc.

The surface finish of a product is usually measured in terms of a parameter known as surface roughness. It is considered as an index of product quality [3]. Better surface finish can bring about improved strength properties such as resistance to corrosion, resistance to temperature, and higher fatigue life of the machined surface [4,5]. In addition to strength properties, surface finish can affect the functional behaviour of machined parts too, as in friction, light reflective properties, heat transmission, ability of distributing and holding a lubricant etc. [6,7]. Surface finish also affects production costs [3]. For the aforesaid reasons, the minimization of the surface roughness is essential which in turn can be achieved by optimizing some of the cutting parameters.

Tool wear is an inherent phenomenon in every traditional cutting operation. Researchers strive towards elimination or minimization of tool wear as tool wear affects product quality as well as production costs. In order to improve tool life, extensive studies on the tool wear characteristics have to be conducted [8]. Some of the factors that affect tool wear and surface roughness are machining parameters like cutting speed, feed, depth of cut etc., tool material and its properties, work material and its properties and tool geometry. Minimal changes in the above mentioned factors may bring about significant changes in the product quality and tool life [3].

In order to achieve desired results, optimization is needed. Optimization is the science of getting most excellent results subjected to several resource constraints. In the present world scenario, optimization is of utmost importance for organizations and researchers to meet the growing demand for improved product quality along with lesser production costs and faster rates of production [9]. Statistical design of experiments is used quite extensively in optimization processes. Statistical design of experiments refers to the process of planning the experiments so that appropriate data can be analysed by statistical methods, resulting in valid and objective conclusions [10]. Methods of design such as Response Surface Methodology (RSM), Taguchi's method, factorial designs etc., find unbound use nowadays replacing the erstwhile one factor at a time experimental approach which more costly as well as time-consuming [11].

Neseli et. al [4] used RSM method and Nose radius, approach angle and rake angle as the input variables and found that the nose radius has the most significant effect on surface roughness. Nanavati and Makadia [3] used feed, cutting speed and tool nose radius as predictors in the RSM method and determined that feed was the most significant factor affecting the surface roughness followed by the tool nose radius. Yang and Tarng [2] used the Taguchi method to find the optimal cutting parameters. A study conducted by Bouacha [5], showed that feed rate was the most influential parameter in determining surface finish of a product followed by the cutting speed. Halim [14] found that tool wear is most significantly affected by the depth of cut while other factors were seemingly insignificant. The present study uses cutting speed, feed, and depth of cut as the machining parameters and the objective is to optimize these parameters so as to find the minimum surface roughness and tool wear.

1.3 OBJECTIVES OF PRESENT WORK

Tool wear is an inherent occurrence in any machining process. Wear affects tool life and product quality. Hence, improvements have to be made in order to increase tool life.
Surface finish is also an important aspect of a machined product.

a) To study the influence/effect of machining parameters viz. speed, feed and depth of cut, on the tool wear of a clamped insert-type tool.
b) To study the influence/effect of machining parameters viz. speed, feed and depth of cut, on the surface roughness of machined material.
c) To determine optimum machining parameter settings for the chosen tool/work combination so as to minimize the tool wear and surface roughness using RSM.
d) To develop an empirical model for the Surface Roughness and the Tool Wear for the chosen tool/work combination within the specified domain of parameters.

Chapter 2 LITERATURE REVIEW

2.1 INTRODUCTION

The ensuing chapter covers published work of researchers pertaining to the turning process in order to optimize parameters. Specifically, theory and information relating to the experiment and the turning process is presented. The scope of the review also extends to various optimization techniques that are used to obtain optimal solution mainly focusing on the Response Surface Method.

2.2 THE TURNING OPERATION

The turning operation is a basic metal machining operation that is used widely in industries dealing with metal cutting [1]. In a turning operation, a high-precision single point cutting tool is rigidly held in a tool post and is fed past a rotating work piece in a direction parallel to the axis of rotation of the work piece, at a constant rate, and unwanted material is removed in the form of chips giving rise to a cylindrical or more complex profile [12,13]. This operation is carried out in a Lathe Machine either manually under an operator's supervision, or by a controlling computer program. There are two types of motion in a turning operation. One is the cutting motion which is the circular motion of the work and the other is the feed motion which is the linear motion given to the tool. The basic turning operation with the motions involved is shown in Fig 1 and Fig 2, figures from [14]. Fig 3 from [15] shows a single point cutting tool and its nomenclature.

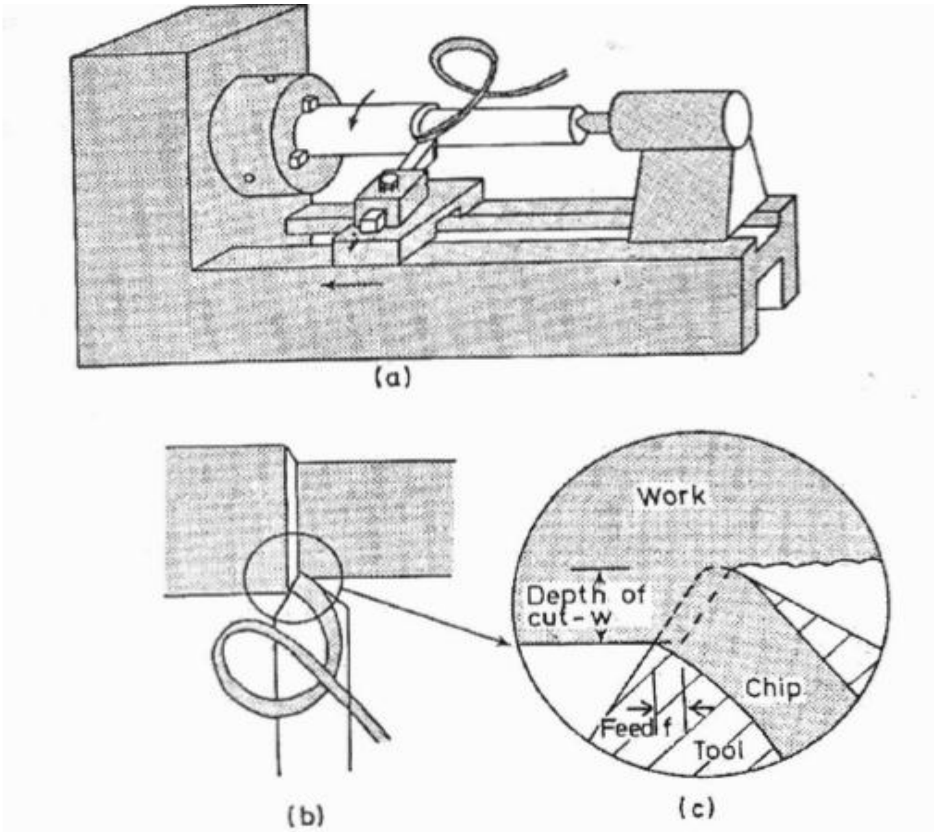


Fig 1: Basic turning operation in Lathe [14]

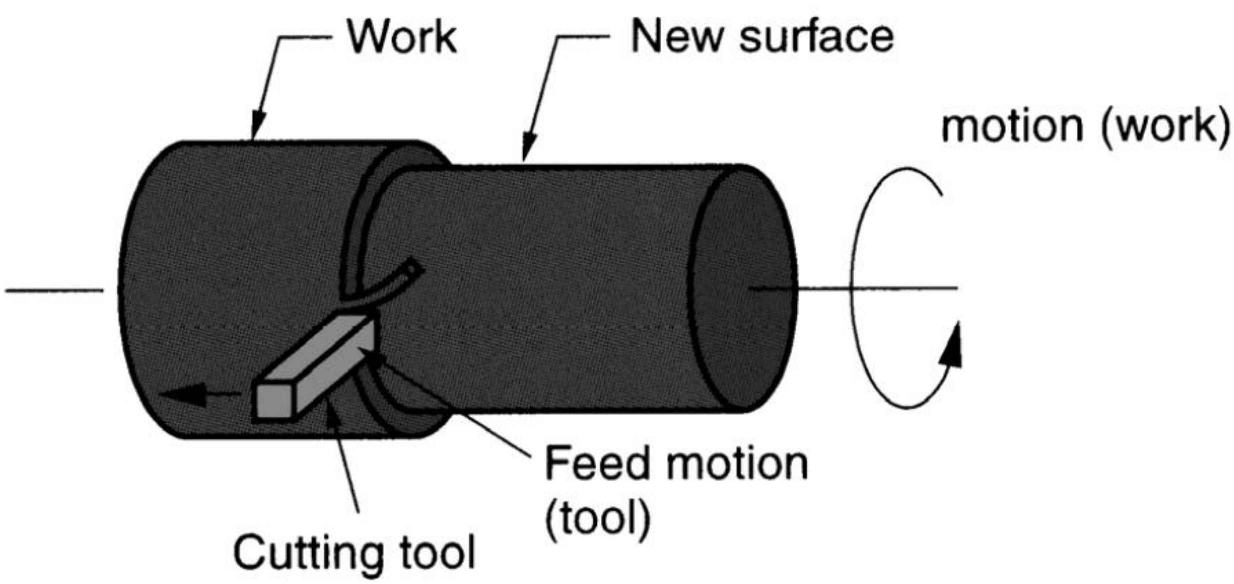


Fig 2: Motions in turning operation [14]

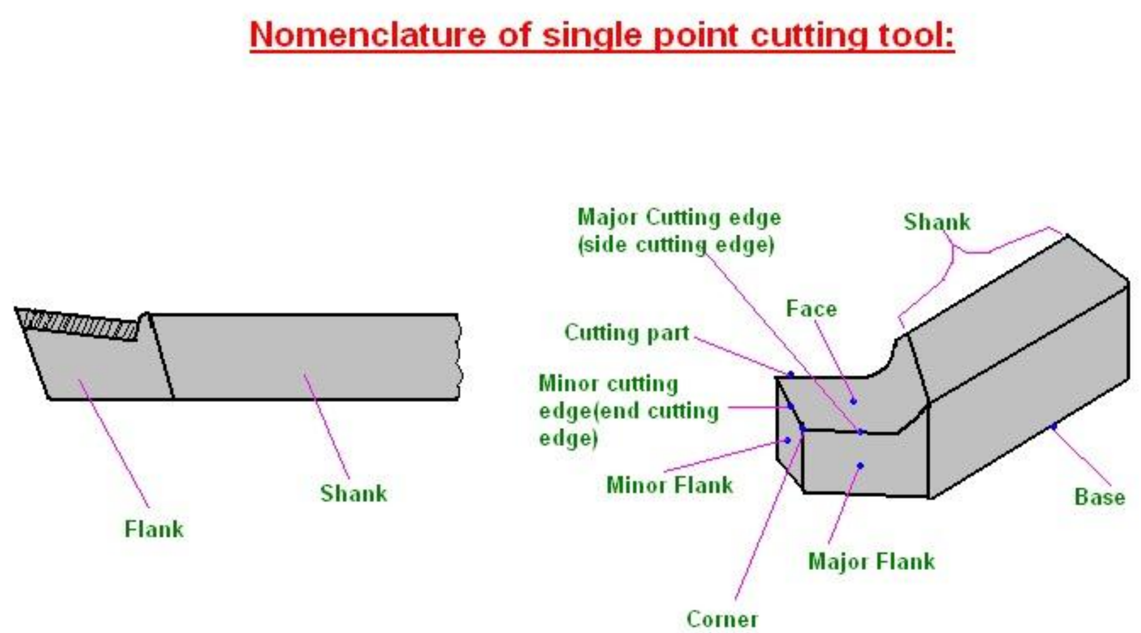


Fig 3: Single point cutting tool using in turning and its nomenclature [15]

2.3. MACHINING PARAMETERS

The turning operation is governed by geometry factors and machining factors. This study consists of the three primary adjustable machining parameters in a basic turning operation viz. speed, feed and depth of cut. Fig 4 from [2] shows these three parameters. Material removal is obtained by the combination of these three parameters [14]. Other input factors influencing the output parameters such as surface roughness and tool wear also exist, but the latter are the ones that can be easily modified by the operator during the course of the operation [15].

2.3.1 Cutting Speed

Cutting speed may be defined as the rate at which the uncut surface of the work piece passes the cutting tool [1]. It is often referred to as surface speed and is ordinarily expressed in m/min, though ft./min is also used as an acceptable unit [1,16]. Cutting speed can be obtained from the spindle speed. The spindle speed is the speed at which the spindle, and hence, the work piece, rotates. It is given in terms of number of revolutions of the work piece per minute i.e. rpm. If the spindle speed is 'N' rpm, the cutting speed V_c (in m/min) is given as

$$V_c = \frac{\pi D N}{1000} \qquad \text{---------------------- (1)}$$

where, D = Diameter of the work piece in mm

2.3.2 Feed

Feed is the distance moved by the tool tip along its path of travel for every revolution of the work piece. It is denoted as 'f' and is expressed in mm/rev. Sometimes, it is also expressed in terms of the spindle speed in mm/min as

$$F_m = f N \qquad \text{---------------------- (2)}$$

where, f = Feed in mm/rev

N = Spindle speed in rpm

2.3.2 Depth of cut

Depth of cut (d) is defined as the distance from the newly machined surface to the uncut surface. In other words, it is the thickness of material being removed from the work piece. It can also be defined as the depth of penetration of the tool into the work piece measured from the work piece surface before rotation of the work piece. The diameter after machining is reduced by twice of the depth of cut as this thickness is removed from both sides owing to the rotation of the work.

$$d = \frac{D_1 - D_2}{2} \qquad \text{---------------------- (3)}$$

where, D_1 = Initial diameter of job

D_2 = Final diameter of job

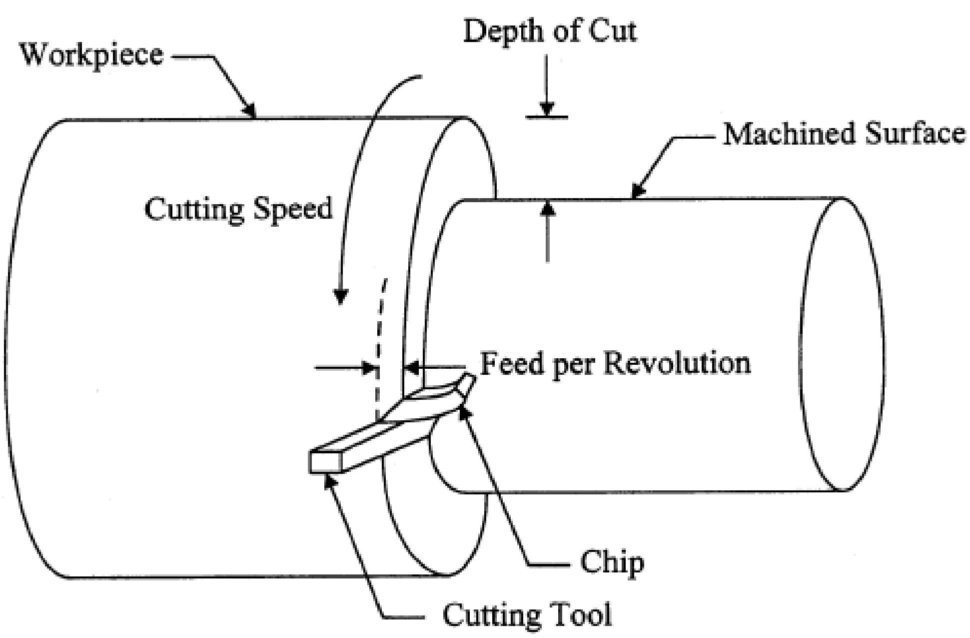


Fig 4: The adjustable machining parameters [2]

2.4 CUTTING TOOL

A cutting tool can be defined as a part of a machine tool that is responsible for removing the excessive material from the work piece by direct mechanical abrasion and shear deformation [13,17]. According to Choudhury et. al [16] and Schenider [18], an efficient cutting tool should have the following characteristics –

a) Hardness: The tool material should be harder than the work material.
b) Hot hardness: The tool must maintain its hardness at elevated temperatures encountered during the machining process.
c) Wear Resistance: The tool should have served to its acceptable level of life before it wears out and needs to be replaced.
d) Toughness: The material should be strong enough so as to withstand shocks and vibrations. During interrupted cutting, the tool should not chip or fracture.

For the ensuing study, the cutting tool used will be a clamped insert-type tool.

2.4.1 Cutting Tool Insert

The term 'Insert' refers to the condition when a cutting tool is screwed or clamped to a holder which is in turn fixed to the tool post. Inserts are clamped through various locking mechanisms [19]. The advantage of inserts is that when one particular edge is worn out, it can be rotated to present a new cutting edge. In certain cases, if the geometry allows, after all such edges have been used up; the insert can be removed, turned upside down and clamped again to reveal a fresh array of cutting edges. Inserts come in a varied range of shapes and sizes some of which are shown in Fig 5 from [14].

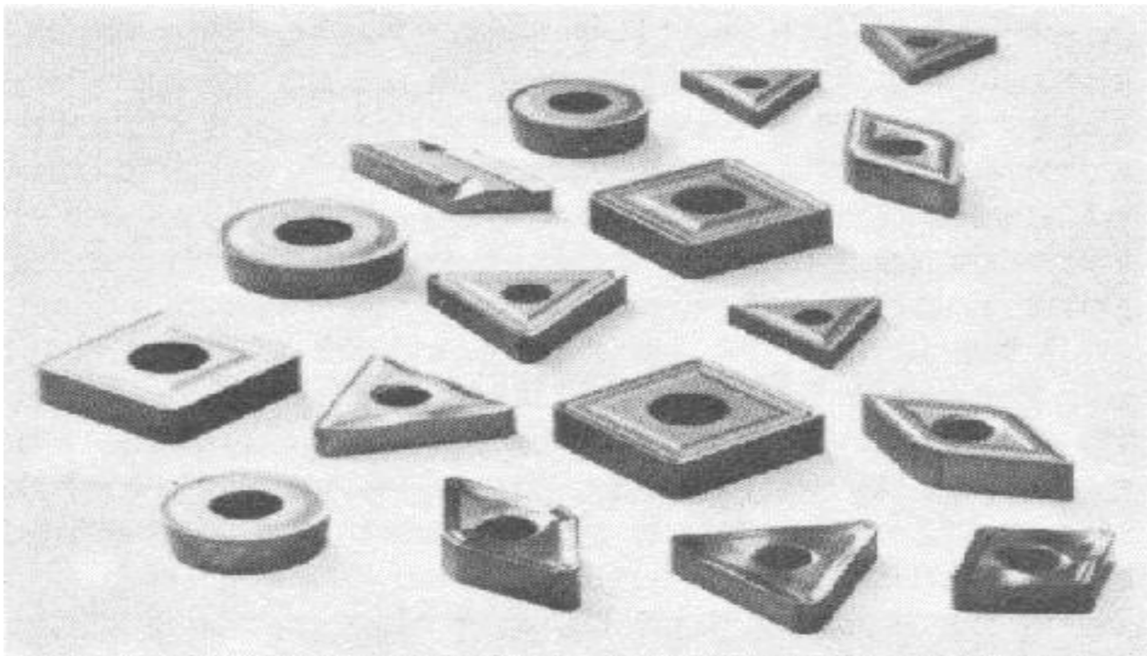


Fig 5: Various shapes of cutting tool inserts [14]

2.4.1.1 Insert Material

There is a large variety of cutting tool materials that are available, each having its own specific properties and performance abilities. Examples of insert materials are Carbides, HSS, CBN, Diamond, Carbon speed steels etc. Carbide tools find common use in the metal cutting industry due to their ability to machine at elevated temperatures and higher speeds [17].

2.4.1.2 Insert Coating

The cutting tool insert is coated to add improvement factors to it [19]. There is a variety of coating materials each having their own specific applications and advantages. Physical vapour deposition (PVD) method is one of the widely used methods used to achieve the coating of a cutting tool. Another technique is Chemical vapour deposition (CVD). The CVD coating technique requires higher temperature which makes it unfeasible for coating tool steels. Usage of PVD method in order to apply Titanium Nitride (TiN) can be achieved at a much lower temperatures (around 4000^0 C) [20]. PVD also facilitates the formation of sharper corners and lower coefficient of friction [17].

2.5 TOOL WEAR

Tool wear is an inherent occurrence in every conventional machining process. Bin Halim said that the tool wear is analogous to the gradual wear of the tip of a pencil [14]. It is the gradual failure of cutting tools due to regular operation [17]. The tool wear rate is dependent on the tool material itself, the tool shape and geometry, work piece material etc. The foremost important factors affecting the tool wear which can be easily controlled are process parameters.
A key factor in the rate of tool wear of materials is the temperature achieved during machining. The general idea is that energy expended in cutting is converted into heat and that a large fraction of it is taken away in the chip. This results in about 20% of the heat generated going into the cutting tool. The following types of tool wear modes can be observed [15]:

(a) Flank

(b) Notch

(c) Crater

(d) Edge rounding

(e) Edge chipping

(f) Edge cracking

(g) Catastrophic failure

Some of these tool wear modes can be evident from Fig 6 from [17].

Flank wear and Crater wear are the two major types of wear which are present almost instantaneously even for low machining times. This study will be focusing on these two types only as our machining time was chosen to be 1 min.

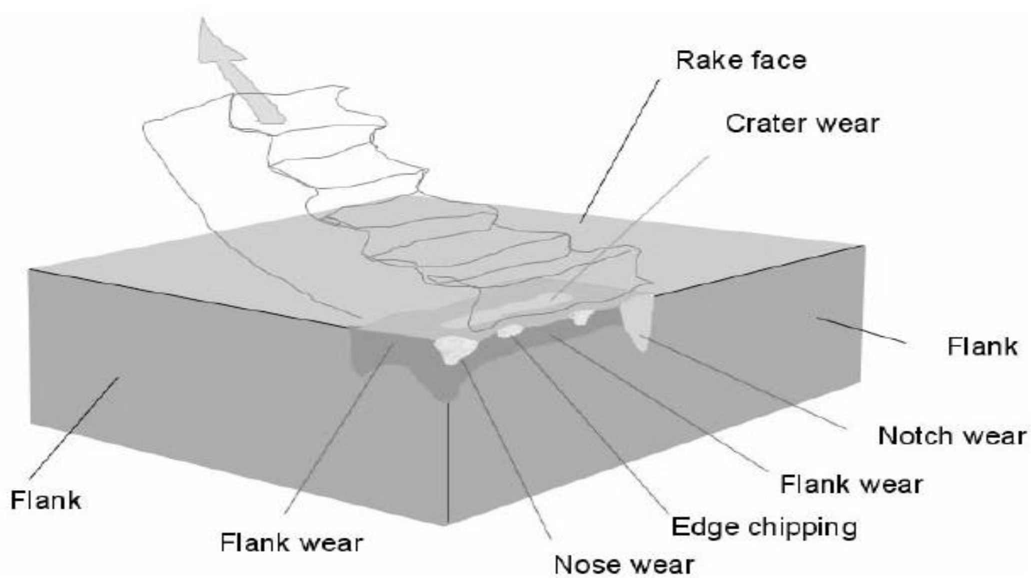


Fig 6: Different modes of tool wear [17]

2.5.1 Flank Wear

Flank wear (Fig 7, figure from [17]) is the wear that occurs on the flank surface or flank faces of the cutting tool. This occurs due to direct mechanical abrasion and friction between the flank surface and the work piece during the operation [21]. The width of the wear land is a straightforward measure of the flank wear [14]. The width is denoted as VB. The tool life is conventionally considered to be over when the average flank wear land V_B reaches 300 µm or the maximum flank wear land VB_{max} becomes 600 µm [21]. Choudhury and Srinivas [22], found that cutting speed and diffusion coefficient index have the most notable effect on the flank wear, followed by feed and depth of cut.

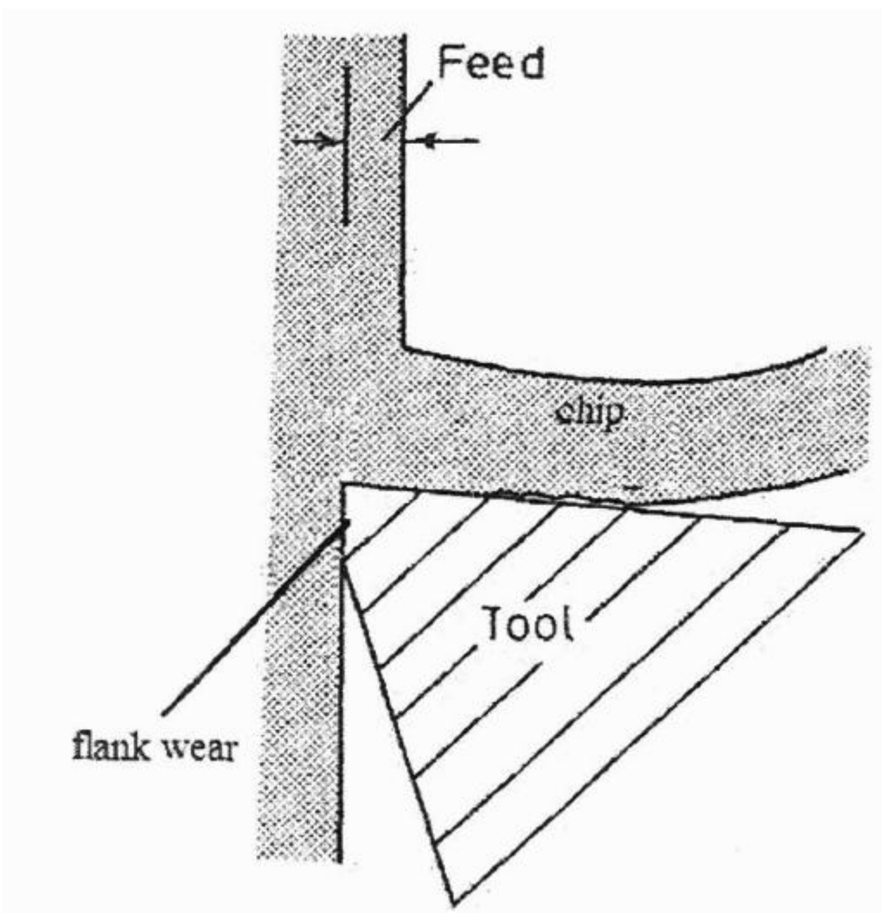


Fig 7: Flank wear [17]

2.5.2 Crater Wear

Crater wear (Fig 8, figure from [17]) is the wear that takes place on the rake face or the top face of the cutting tool. It occurs parallel to the principal cutting edge. This type of erosion occurs due to the rubbing of the chip on the rake face during machining [14]. According to Kalpakjian and Schmid [19], the most notable factors that affect the crater wear phenomena are temperature occurring at the chip-tool interference and the chemical affinity between the tool and work materials at the elevated temperatures encountered during machining. Factors affecting flank wear also influence crater wear [17]. B.V. Manoj Kumar, J. Ram Kumar and Bikramjit Basu [23], found out during the dry machining of boiler steel using TiCN-Ni-WC cermet inserts that crater wear increases significantly with cutting speed and feed.

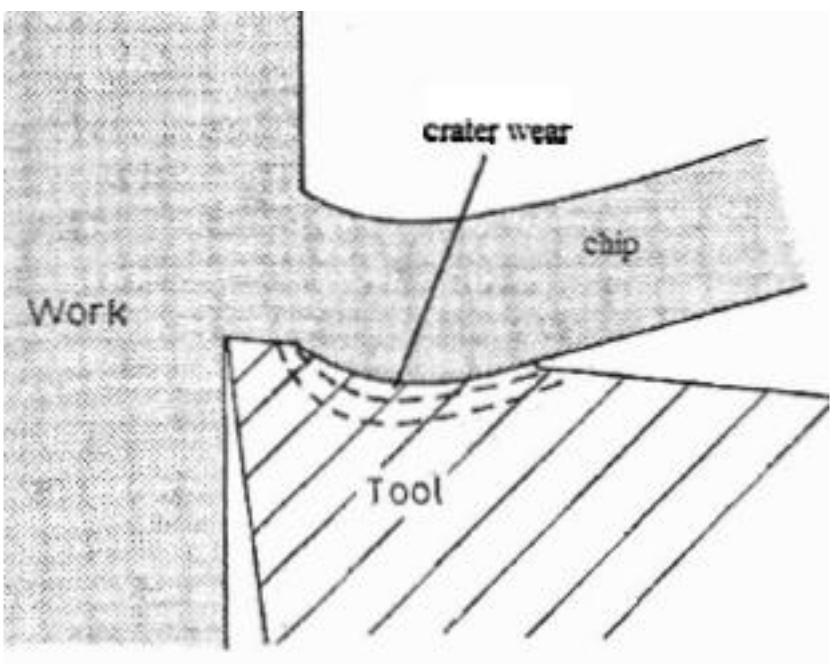


Fig 8: Crater wear [17]

2.6 SURFACE ROUGHNESS

Surface roughness is a measure of the surface finish of a product and an index of the product quality [3]. Surface roughness is a measurement of the small scale variations in the height of a physical surface [14]. It is expressed in various ways and methods, like arithmetic mean or centre-line average (Ra), Root-mean square average (Rq), maximum peak (Ry), ten-point mean roughness (Rz), maximum valley depth (Rv), maximum height of profile (Rt = Rp – Rv) etc. Out of all these, the most commonly used indicator for surface roughness is Ra.

Ra, or the arithmetic mean value, previously known as AA (Arithmetic Average) or CLA (Centre-Line Average) is the arithmetic mean of deviations of a series of points from the centre line or datum line. The datum line is such that sum of the areas under the profile above the datum will be equal to the sum of areas below the datum. Generally, surface roughness is expressed in microns (μm).

$$Ra = \frac{a+b+c+d+e+f \ldots.}{n} \qquad \text{-------------- (4)}$$

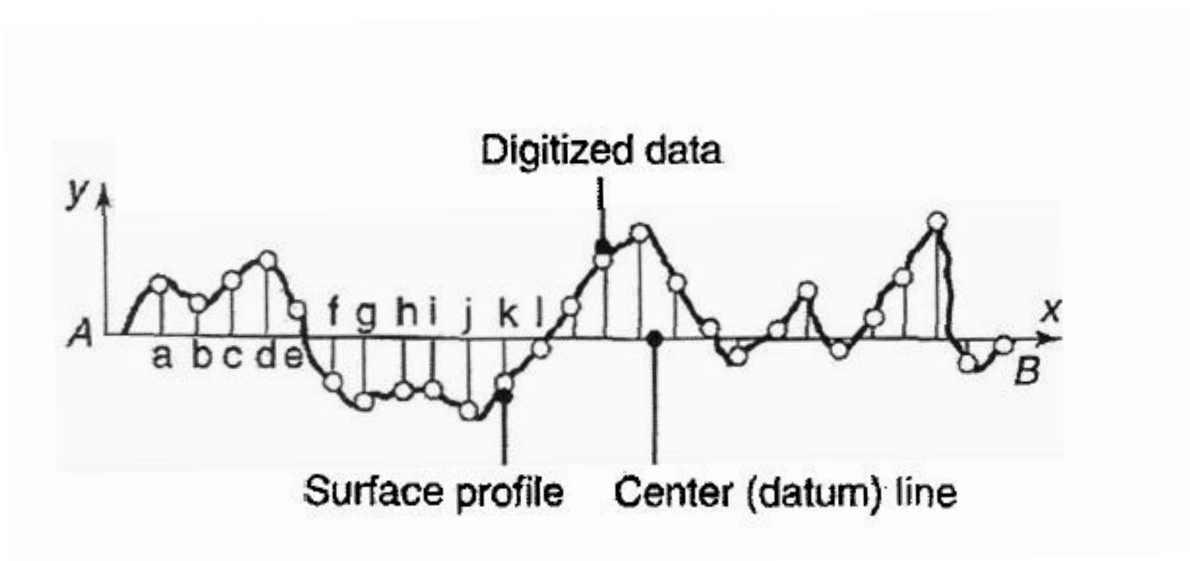


Fig 9: Co-ordinates used for Surface Roughness Measurement using Equation 4 [17]

Studies by Sahin Y. and Motorcu A.R., have shown that surface roughness is mostly dependent on feed rate which is the dominating factor [24].

The surface roughness is usually measured in a direct way by the use of devices called Profilometer. The Profilometer is a stylus probe instrument in which the stylus mounted in the pick-up unit traverses across the machined surface by means of a motor drive. The pick-up receives ad rectifies the output which is further amplified and the average height of the roughness is reported digitally. One of the common types of Profilometer available is the Taylor-Hobson Talysurf. It works on the principle of carrier modulation [25].

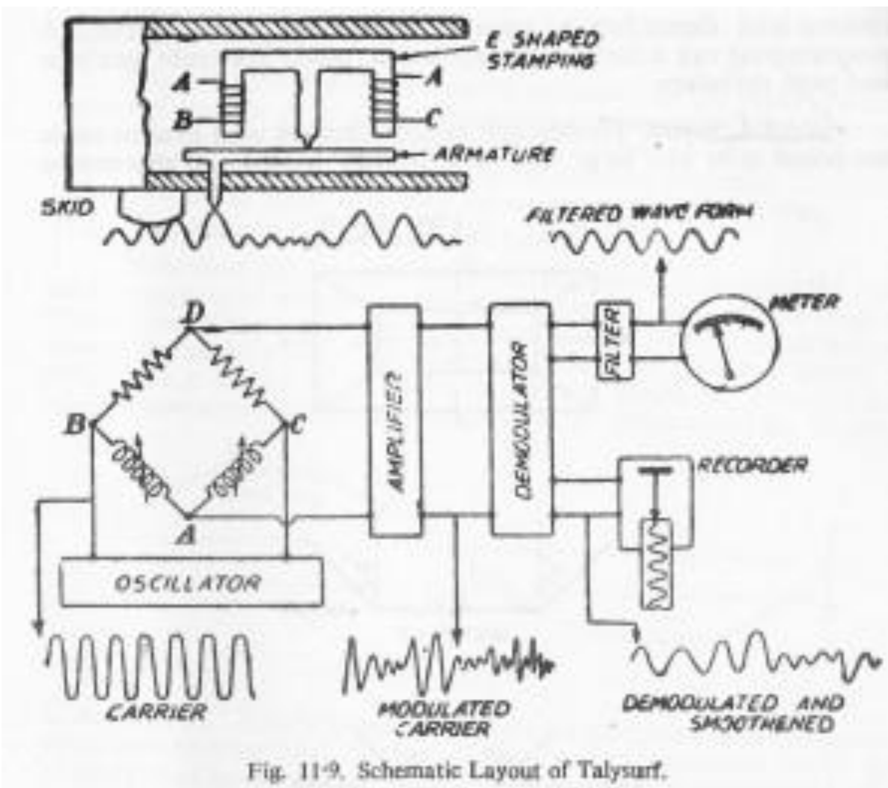


Fig 10: Schematic Layout of Talysurf [25]

The schematic layout of the Talysurf is shown in the above figure from [25]. It consists of a diamond stylus with a tip radius of 0.002mm. The arm carrying the stylus forms an armature which pivots about the center leg of E-shaped stamping. Coils are wound around the two outer legs of the E-shaped stamping and they carry alternating current. These two coils with other two resistances form an oscillator. Movements in the stylus cause a variation in the air gap between the armature and the stamping thereby modulating the amplitude of the alternating current. The demodulator demodulates the signals such that the current becomes directly proportional to only the vertical displacements of the stylus. The output is fed to a recorder which records and produces the numerical output [25].

2.7 DESIGN OF EXPERIMENTS

Design of experiments (DOE) is a structured method that is used to identify relationships between several input variables and output responses. With the help of DOE, the resources needed to carry out the experiment can be optimized [14]. Hence, it finds wide use in R & D studies. A few methods used as DOE are Taguchi Method, Response Surface Method and Factorial Designs. We will be focusing on the Response Surface Methodology during the ensuing study.

2.7.1 Response Surface Methodology (RSM)

Response Surface Method (RSM) is a collection of mathematical and statistical tools which are useful for the modelling and analysis of problems in which an output response of interest is influence by several input variables and our objective is to optimize (minimize or maximize based on the need) the response [10]. It is a method which was developed by Box and

Wilson in the early 1950's [9]. It is capable of establishing causal relationships between input and output variables.

For 'n' number of measurable input variables, the response surface can be given as –

$$Y = f(x_1, x_2, x_3, x_4 \ldots x_n) + \varepsilon \qquad \text{-----------(5)}$$

Where, $x_1 \ldots x_n$ are the independent input parameters and ε is the random error.

Y is the output or response variable which has to be optimized.

In a turning operation with three input variables, the response function can be written as –

$$Y = f(x_1, x_2, x_3) + \varepsilon \qquad \text{----------- (6)}$$

Where, $x_1 = \log V_c$, $x_2 = \log f$, and $x_3 = \log d$. $Y = \log Ra$ and ε is the random error.

RSM is generally employed through multiple regression models. Our goal is to find a suitable approximation for the response function which can be achieved by the regression models.

For example, the first order or linear multiple regression model can be used –

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad \text{----------- (7)}$$

For better approximation, interaction terms can be included –

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \qquad \text{----------- (8)}$$

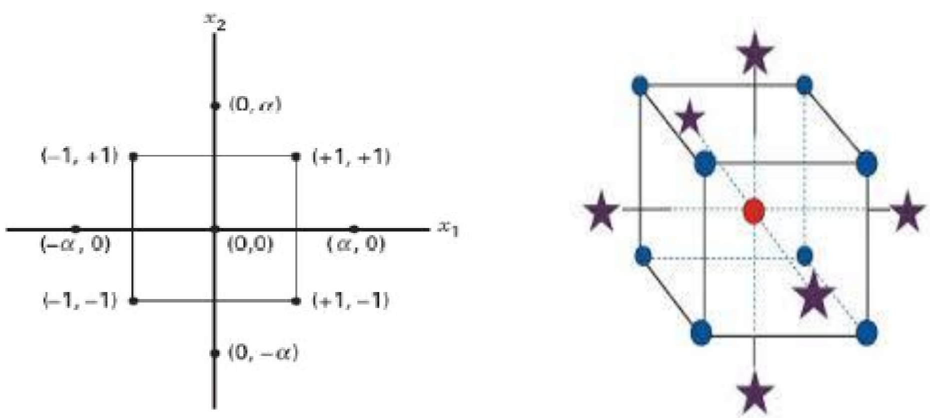
The second order or quadratic regression model includes the square terms in addition to the terms above –

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \text{ ---(9)}$$

The quadratic model given in Equation 9 is generally utilized in RSM problems, the ease being that there are some nice designs available for fitting quadratic models ex. Central Composite Design (CCD) and Box-Behnken Design.

2.7.1.1 Central Composite Design (CCD)

CCD is one of the most popular designs for fitting the second-order models. Generally, the CCD consists of a 2^k factorial design with n_j runs, 2k axial or star runs, and n_c centre runs [26]. The figure below (Fig 11) from [26] shows the CCD for k = 2 and k = 3 factors.



(a) k = 2 **(b)** k = 3

Fig 11: Central Composite Design for 2-factors and 3-factors [26]

First, a 2k first order model is used. If the model shows a lack of fit, then axial and center runs are added to incorporate the quadratic terms in the model [26]. It is important to select the value of α for the axial runs. If α = 1, the design is said to face-centered. The number of center points is also to be selected. For a CCD with 3 input parameters, 6 centre points are generally chosen to get 20 as the total number of runs including 8 cube points (cube corners and 6 axial/star points (Fig b)

Chapter 3 MATERIALS AND METHODS

3.1 WORK MATERIAL

The work piece used for the concluded experiment was AISI 202 grade Austenitic stainless steel. There are two series of Austenitic stainless steels – 300-series and 200-series. 300 series steels find most wide use around the world but 200 series have become very popular in the Asian subcontinent as an alternative to the 300 series to counter the increase in prices of Nickel [27]. Grade 202 steel can be made into plates, sheets and coils and finds extensive use in restaurant equipment, cooking utensils, sinks, automotive trims, architectural applications such as doors and windows, railways cars, trailers, horse clamps etc. [28]

Table 1: Chemical composition (wt %) of AISI 202 Steel

Element	**Wt %**
Iron, Fe	68
Chromium, Cr	17-19
Nickel, Ni	4-6
Manganese, Mn	7.5-10
Silicon, Si	1
Nitrogen, N	0.25
Carbon	0.15
Phosphorous, P	0.06
Sulphur, S	0.03

Table 2: Mechanical Properties of AISI 202 Steel

Property	Value
Tensile Strength	515 MPa
Yield Strength	275 Mpa
Elastic Modulus	207 Gpa
Poisson's Ratio	0.27-0.30
Elongation at break	40%

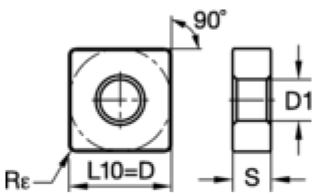
3.2 INSERT MATERIAL

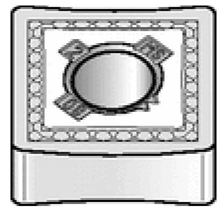
The tool insert chosen was a coated carbide tool (Kennametal make) whose specifications are shown below. Coated carbide tools are found to perform better than uncoated ones [11].

Table 3: Specification of Cutting Tool

ISO Catalog Number	ANSI Catalog Number	Grade	Dimensions									
			D		L10		S		R_{ε}		D1	
			mm	in	mm	in	mm	in	mm	in	mm	in
SNMG 120408	SNMG 432MS	KCU25	12.70	0.5	12.70	0.5	4.76	0.1875	5.16	0.203		

The chosen insert (Fig 12 from [29]) was a square type negative insert meaning that it was rotatable and reversible so that a total number of 8 cutting edges can be generated. KCU25 takes advantage of PVD coating technology including special surface treatments that improve machining performance in high-temperature materials [29]. The coating on the insert is TiAlN (Titanium Aluminium Nitride).





(a) **(b)**

Fig 12: Selected cutting tool insert [29]

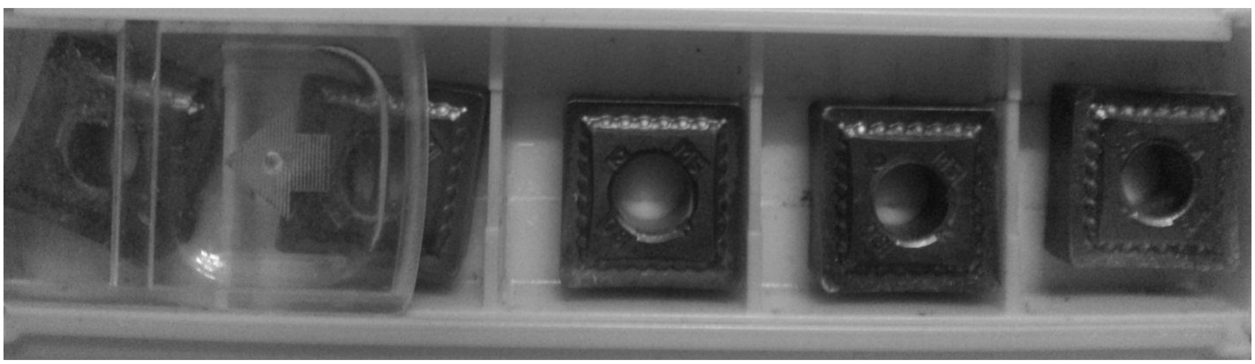


Fig 13: Set of cutting inserts used in the experimentation

3.3 EXPERIMENTAL SETUP AND INITIAL PREPARATION

A centre lathe was used to carry out the machining. The insert was clamped in a holder and mounted on the tool post. The job was held rigidly by the chuck of the lathe. Centre drilling was done and the job was held at the other end by the tail stock and a skin pass was carried out. The setup was hence complete and the runs could be carried out from here.

Fig 14: Experimental Setup

Fig 15: Mounting of tool and workpiece

3.4. CUTTING CONDITION

Dry cutting environment was used for the experimentation process. Dry cutting process is one that uses no coolant during machining. By the use of dry cutting, costs of cutting fluid were alleviated. Cutting fluids have corrosive effects and non-environment-friendly. Dry cutting reduces machining cost and is environment friendly. Also, inserts perform better at higher cutting temperatures achieved during dry cutting [14].

3.5 MEASUREMENT OF SURFACE ROUGHNESS

Surface roughness has been precisely measured with the help of a portable stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+, UK). Measurements were taken at different locations and the average was reported for each run.

Fig 16: Setup of Talysurf for measurement of Surface Roughness

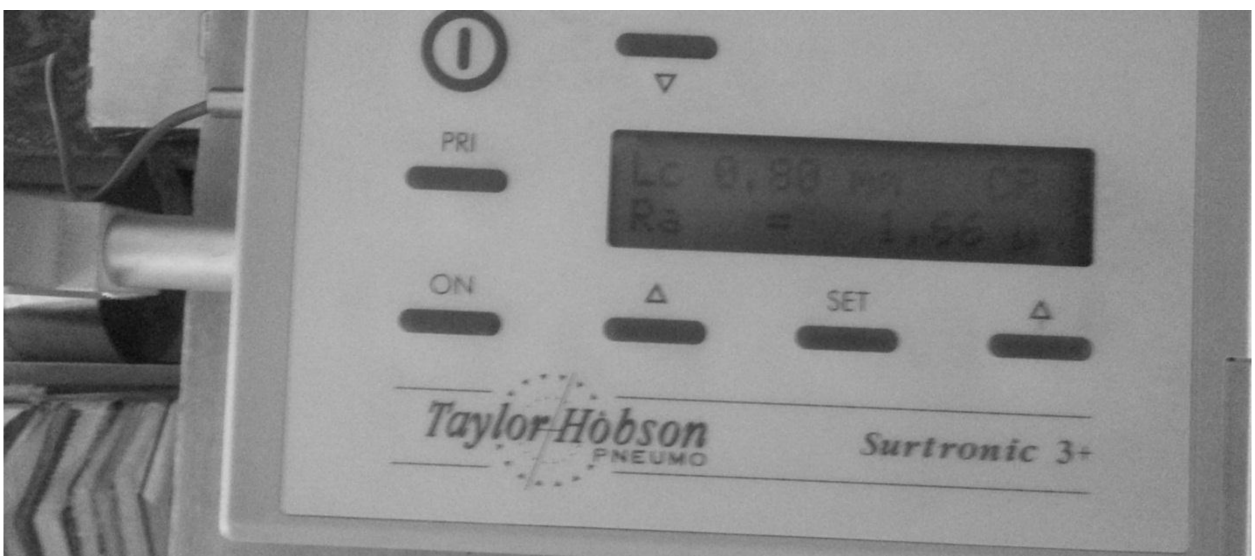


Fig 17: Reading shown in Talysurf

3.6 MEASUREMENT OF TOOL WEAR

A new cutting edge was used for each run. The resulting tool wear was measured using a Toolmaker’s Microscope (Fig 18) with digital read-out device (Fig 20). A view of the tool insert through the eyepiece is also shown in Fig 19.

Table 4: Specification of Toolmaker’s Microscope

1.1	Nr	14832
DDR	Made in the CDR	
1554	Achsenhohe 42.52 mm	

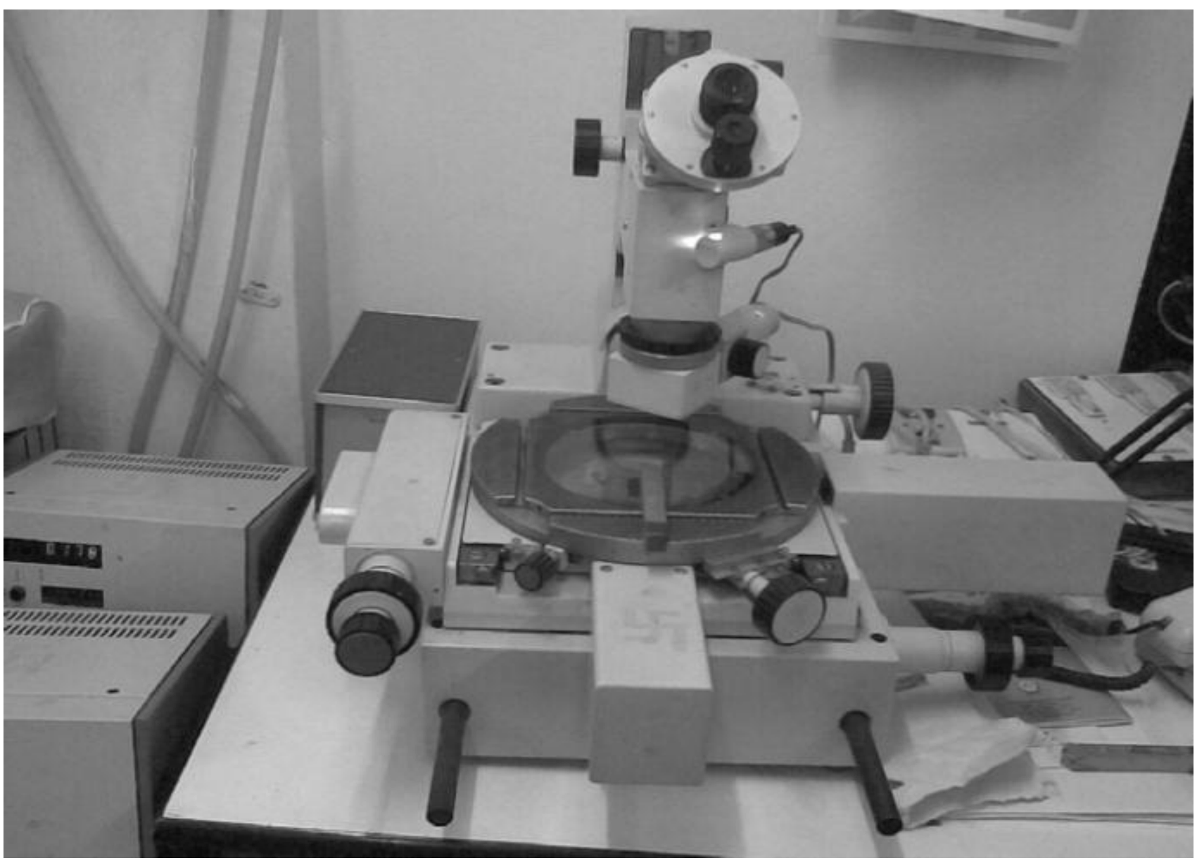


Fig 18: Toolmakers’ Microscope

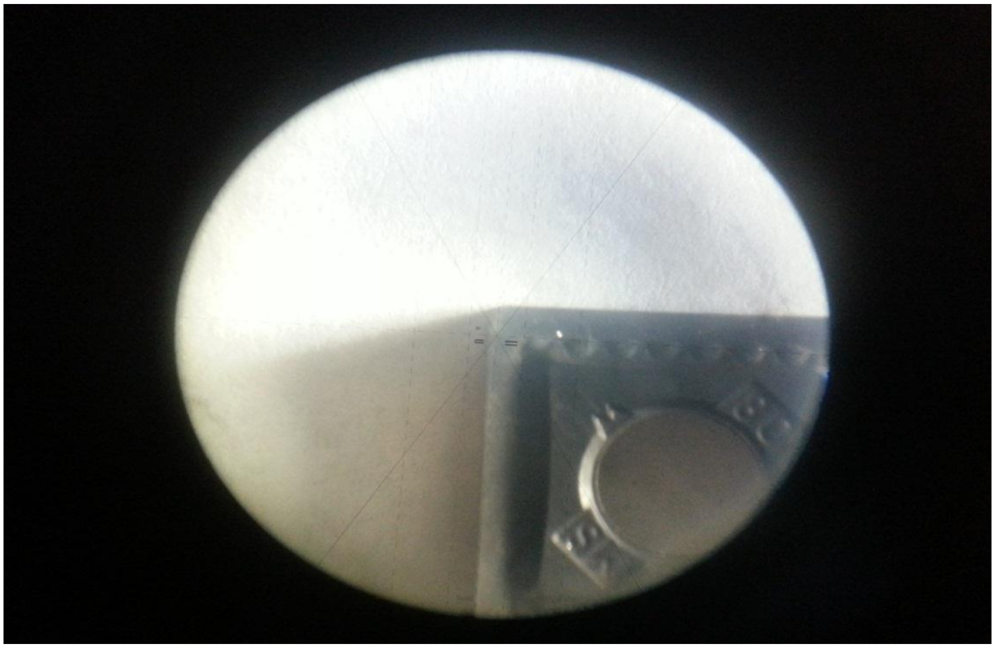


Fig 19: View of the insert through the eyepiece

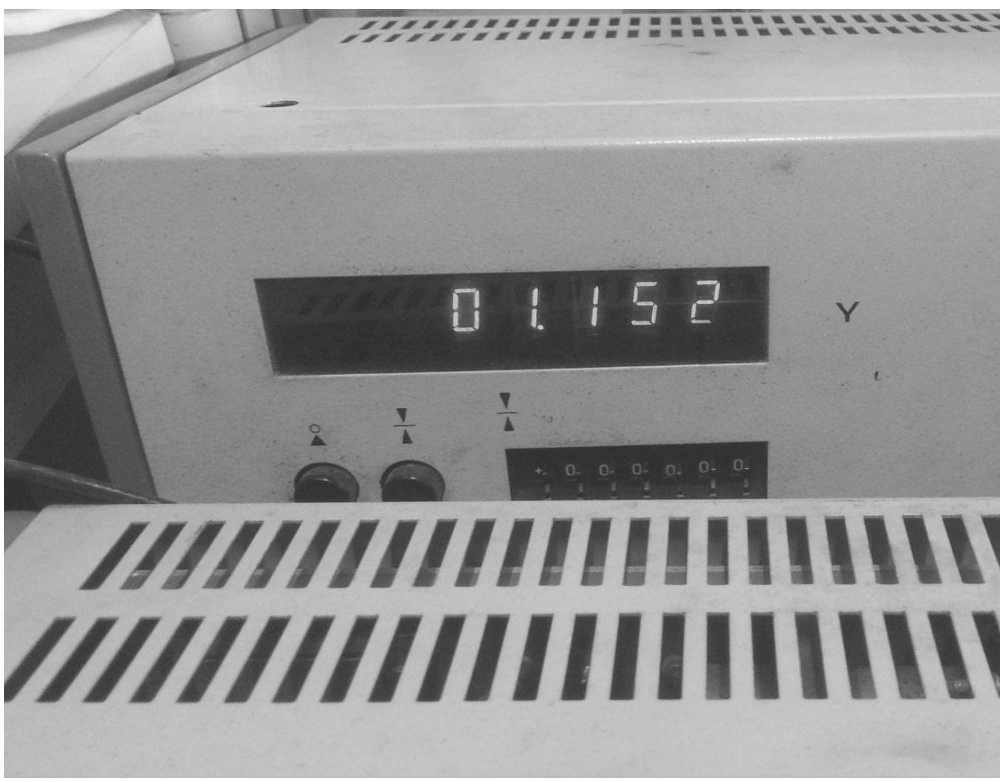


Fig 20: Digitized reading of tool wear

3.7 PROCESS PARAMETERS

The following table (Table 5) shows the levels of the cutting parameters chosen.

Table 5: Factors and levels for the Response Surface Study

Code	Parameter	Level (-1)	Level (+1)
A	Cutting Speed (m/min)	66	112
B	Feed (mm/rev)	0.05	0.15
C	Depth of cut (mm)	0.4	0.8

3.8 LAYOUT OF EXPERIMENT FOR RSM

The experiment layout was obtained in accordance with the 3-level full-factorial Central Composite Design with 8 cube points, 6 axial points, 4 centre points, and 2 centre points in axial, resulting in a total of 20 runs. α was chosen as 1 to make the design face centred. Table 6 below contains the experimental layout used.

Table 6: Design Layout/Run Table

StdOrder	RunOrder	PtType	Blocks	Cutting Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)
1	4	1	1	66	0.05	0.4
2	1	1	1	112	0.15	0.4
3	3	1	1	112	0.05	0.8
4	2	1	1	66	0.15	0.8
5	15	0	1	89	0.1	0.6
6	16	0	1	89	0.1	0.6
7	7	1	2	112	0.05	0.4
8	6	1	2	66	0.15	0.4
9	8	1	2	66	0.05	0.8
10	5	1	2	112	0.15	0.8
11	17	0	2	89	0.1	0.6
12	18	0	2	89	0.1	0.6
13	10	-1	3	66	0.1	0.6
14	9	-1	3	112	0.1	0.6
15	13	-1	3	89	0.05	0.6
16	11	-1	3	89	0.15	0.6
17	12	-1	3	89	0.1	0.4
18	14	-1	3	89	0.1	0.8
19	19	0	3	89	0.1	0.6
20	20	0	3	89	0.1	0.6

Chapter 4 RESULTS AND DISCUSSIONS

4.1 EXPERIMENTAL RESULTS

The results obtained from the experimental work are summarized in the Table 7.

Table 7: Results Obtained

StdOrder	RunOrder	Cutting Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Ra (µm)	Flank wear (mm)
1	4	66	0.05	0.4	0.947	0.443
2	1	112	0.15	0.4	1.513	0.768
3	3	112	0.05	0.8	1.353	0.932
4	2	66	0.15	0.8	1.7	1.17
5	15	89	0.1	0.6	0.86	1.629
6	16	89	0.1	0.6	0.887	1.209
7	7	112	0.05	0.4	0.88	0.487
8	6	66	0.15	0.4	1.947	0.57
9	8	66	0.05	0.8	1.893	1.104
10	5	112	0.15	0.8	1.673	1.151
11	17	89	0.1	0.6	1.053	1.844
12	18	89	0.1	0.6	1	1.604
13	10	66	0.1	0.6	1.16	0.928
14	9	112	0.1	0.6	0.96	1.001
15	13	89	0.05	0.6	2.16	0.948
16	11	89	0.15	0.6	2.013	0.859
17	12	89	0.1	0.4	1.413	0.788
18	14	89	0.1	0.8	1.007	1.116
19	19	89	0.1	0.6	0.967	1.807
20	20	89	0.1	0.6	0.96	1.793

4.2 ANALYSIS OF RESULTS AND PLOTS

The results obtained from the experiment were fed into MINITAB ® 17 for further analysis.

4.2.1 ANOVA

The analysis of variance (ANOVA) (shown in Table 8 and Table 9) was used to study the significance and effect of the cutting parameters on the response variables i.e. Ra and Tool wear.

Table 8: ANOVA for Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2.7542	0.30602	3.47	0.033
Linear	3	0.50671	0.1689	1.92	0.191
Cutting Speed	1	0.16078	0.16078	1.82	0.207
Feed	1	0.26018	0.26018	2.95	0.117
Depth of Cut	1	0.08575	0.08575	0.97	0.347
Square	3	1.96078	0.65359	7.41	0.007
Cutting Speed*Cutting Speed	1	0.16281	0.16281	1.85	0.204
Feed*Feed	1	1.68678	1.68678	19.13	0.001
Depth of Cut*Depth of Cut	1	0.02395	0.02395	0.27	0.614
2-Way Interaction	3	0.28671	0.09557	1.08	0.4
Cutting Speed*Feed	1	0.00266	0.00266	0.03	0.865
Cutting Speed*Depth of Cut	1	0.00054	0.00054	0.01	0.939
Feed*Depth of Cut	1	0.2835	0.2835	3.21	0.103
Error	10	0.88184	0.08818		
Lack-of-Fit	5	0.8564	0.17128	33.66	0.11
Pure Error	5	0.02545	0.00509		
Total	19	3.63604			

From Table 7, we can see that the P-Value for the model is 0.033 which is lesser than the significance value of 0.05. Hence, the model is significant. The lack-of-fit has a P-value of 0.11 and hence, it is insignificant, which is desirable. Feed is found to be the most influential parameter affecting the surface roughness with the lowest P-value among all three parameters.

Table 9: ANOVA for Tool Wear

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2.46551	0.273945	2.57	0.049
Linear	3	0.62221	0.207403	1.95	0.186
Cutting Speed	1	0.00154	0.001538	0.01	0.907
Feed	1	0.03648	0.036782	0.34	0.571
Depth of Cut	1	0.58419	0.584189	5.48	0.041
Square	3	1.80619	0.602063	5.65	0.016
Cutting Speed*Cutting Speed	1	0.12033	0.120332	1.13	0.313
Feed*Feed	1	0.20075	0.200745	1.88	0.2
Depth of Cut*Depth of Cut	1	0.13514	0.135143	1.27	0.286
2-Way Interaction	3	0.03711	0.012369	0.12	0.949
Cutting Speed*Feed	1	0.01178	0.011781	0.11	0.746
Cutting Speed*Depth of Cut	1	0.02344	0.023436	0.22	0.649
Feed*Depth of Cut	1	0.00189	0.001891	0.02	0.897
Error	10	1.06518	0.106518		
Lack-of-Fit	5	0.8564	0.157088	2.81	0.141
Pure Error	5	0.27974	0.055948		
Total	19	3.53068			

From the above Table 8, we can see that the P-Value for the model is 0.049 which is lesser than the significance value of 0.05. Hence, the model is significant. The lack-of-fit has a P-value of 0.141 and hence, it is insignificant, which is desirable. Depth of cut is found to be the most influential parameter affecting the stool wear with the lowest P-value (0.041, significant) among all three parameters.

The main effects and interaction effects plots for the surface roughness and the tool wear are shown in Fig 21 – Fig 24.

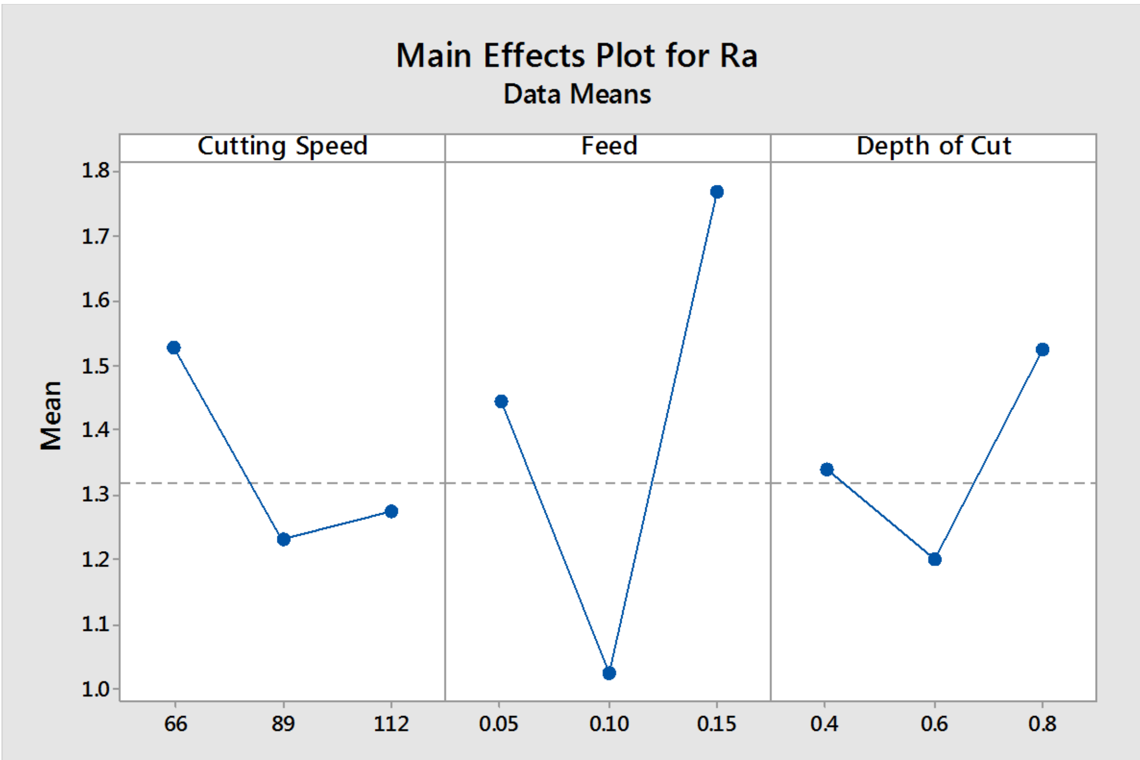


Fig 21: Main effects plot for Ra

The main effects plot for Ra (Fig 21) shows that the surface roughness first decreases sharply with the increase in cutting velocity. After a point, it gradually increases with further increase in cutting velocity. The same happens in the case of feed but the increase after that particular point is very steep. Ra also reduces with increase in depth of cut to that particular level after which it is found to have a steep increase with further increase in the depth of cut.

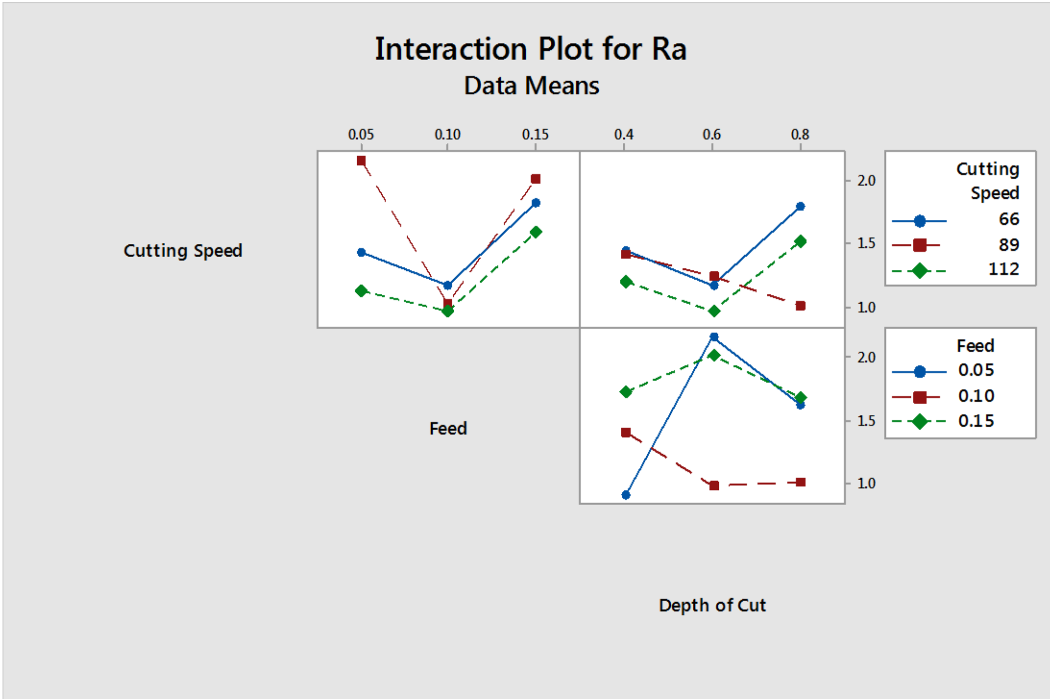


Fig 22: Interaction plot for Ra

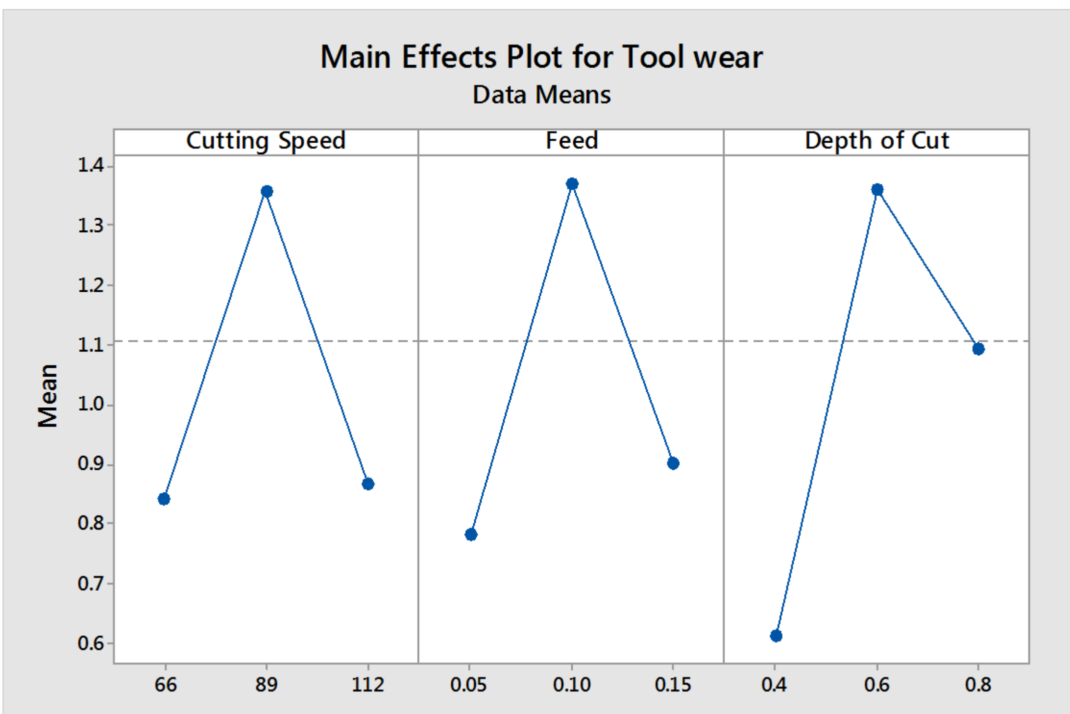


Fig 23: Main effects plot for Tool wear

The main effects plot for tool wear (Fig 23) tells us that a steep rise occurs in the tool wear for an increase in any one of the three parameters up to a certain level with other parameters kept constant. Wear decreases thereafter for rise in any one of cutting speed, feed, or depth of cut with other factors kept constant.

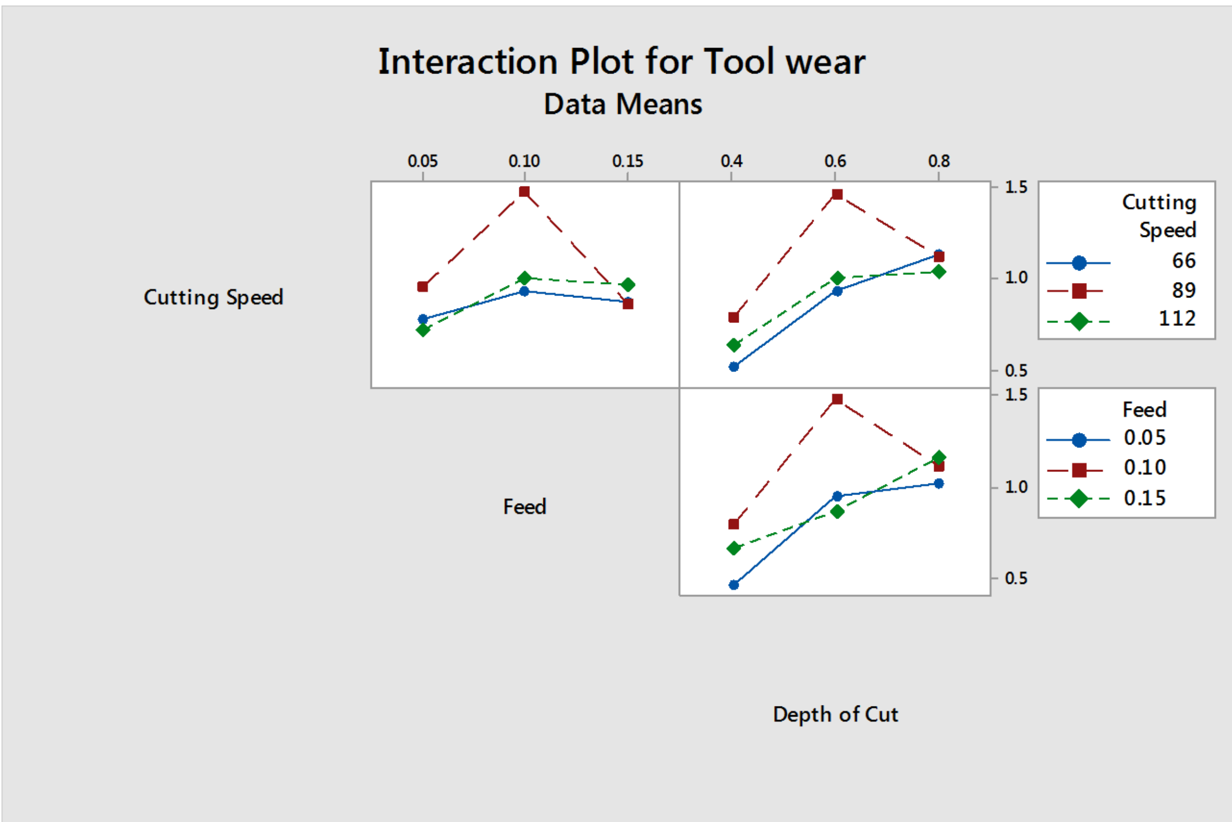


Fig 24: Interaction plot for Tool Wear

The regression coefficients obtained from MINITAB ® 17 are laid out in Tables 10 and 11.

Table 10: Estimated Coded Regression Coefficients for Surface Roughness

Term	Effect	Coef	SE Coef	T-Value	P-Value
Constant		1.094	0.102	10.72	0
Cutting Speed	-0.2536	-0.1268	0.0939	-1.35	0.207
Feed	0.3226	0.1613	0.0939	1.72	0.117
Depth of Cut	0.1852	0.0926	0.0939	0.99	0.347
Cutting Speed*Cutting Speed	-0.487	-0.243	0.179	-1.36	0.204
Feed*Feed	1.566	0.783	0.179	4.37	0.001
Depth of Cut*Depth of Cut	-0.187	-0.093	0.179	-0.52	0.614
Cutting Speed*Feed	0.037	0.018	0.105	0.17	0.865
Cutting Speed*Depth of Cut	-0.017	-0.008	0.105	-0.08	0.939
Feed*Depth of Cut	-0.376	-0.188	0.105	-1.79	0.103

Regression Equation in Un-coded Units:

$$Ra = -1.45 + 0.0758Vc - 49.5f + 5.30d - 0.00046Vc^2 + 313.3f^2 - 2.33d^2 + 0.0519Vc*f - 0.0018Vc*d - 18.8f*d \quad \text{---------} \ (10)$$

Table 11: Estimated Coded Regression Coefficients for Tool Wear

Term	Effect	Coef	SE Coef	T-Value	P-Value
Constant		1.458	0.112	13	0
Cutting Speed	0.025	0.012	0.103	0.12	0.907
Feed	0.121	0.06	0.103	0.59	0.571
Depth of Cut	0.483	0.242	0.103	2.34	0.041
Cutting Speed*Cutting Speed	-0.418	-0.209	0.197	-1.06	0.313
Feed*Feed	-0.54	-0.27	0.197	-1.37	0.2
Depth of Cut*Depth of Cut	-0.443	-0.222	0.197	-1.13	0.286
Cutting Speed*Feed	0.077	0.038	0.115	0.33	0.746
Cutting Speed*Depth of Cut	-0.108	-0.054	0.115	-0.47	0.649
Feed*Depth of Cut	-0.031	-0.015	0.115	-0.13	0.897

Regression Equation in Un-coded Units:

$$\text{Tool Wear} = -6.07 + 0.0746Vc + 20.8f + 9.06 - 0.000395Vc^2 - 108.1f^2 - 5.54d^2 + 0.033Vc*f - 0.0118Vc*d - 1.5f*d \quad \text{------------ (11)}$$

4.2.2 RESIDUAL PLOTS

Fig 25 and Fig 26 display the residual plots for the surface roughness and the tool wear.

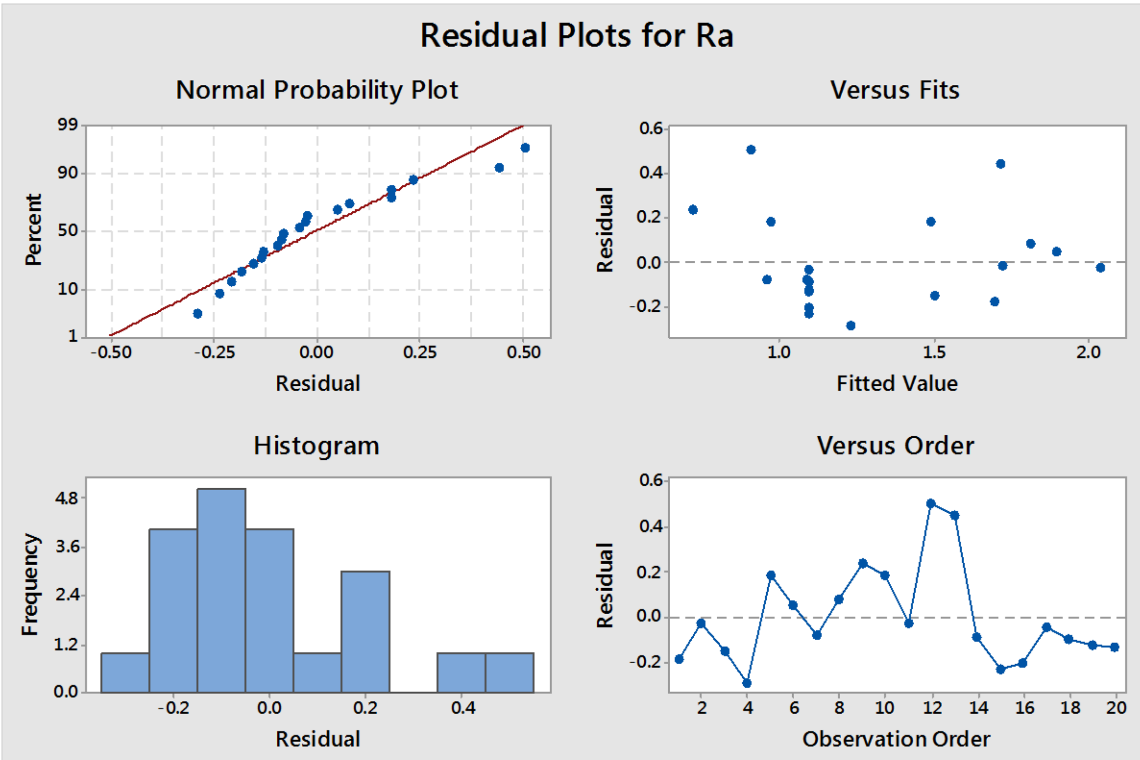


Fig 25: Residual Plots for Ra

The model is adequate as represented by the points falling on a straight line in the normal probability plot. It denotes that the errors are normally distributed. Also, the plot of the residuals versus the predicted response is structure less i.e. containing no obvious pattern.

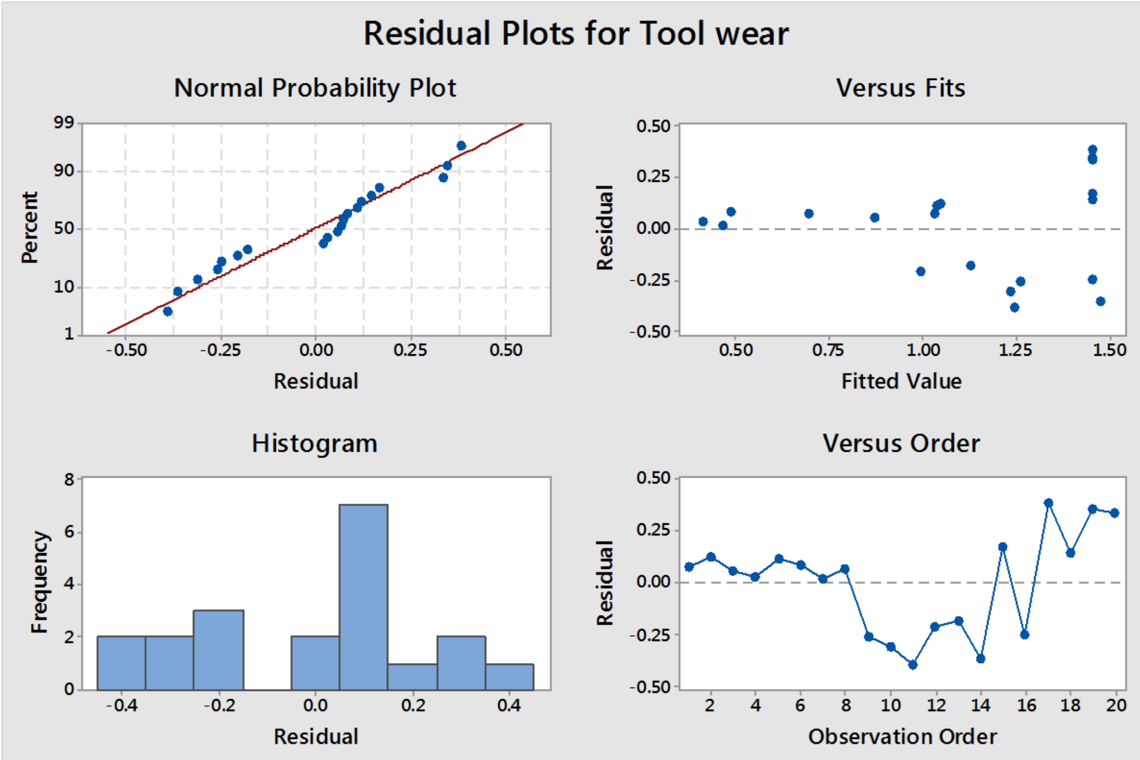


Fig 26: Residual plots for Tool Wear

Again, the model is adequate as represented by the points falling on a straight line in the normal probability plot. It is an indication that the errors are normally distributed which should be the case for a good-fit model. The histogram also shows a nearly bell-shaped normal distribution. Also, the plot of the residuals versus the predicted tool wear is structure less i.e. containing no obvious pattern.

4.2.3 CONTOUR PLOTS AND 3-D SURFACE PLOTS

Contour plots and 3-D surface plots for Surface Roughness and Tool wear are are displayed in Fig 27-Fig 38.

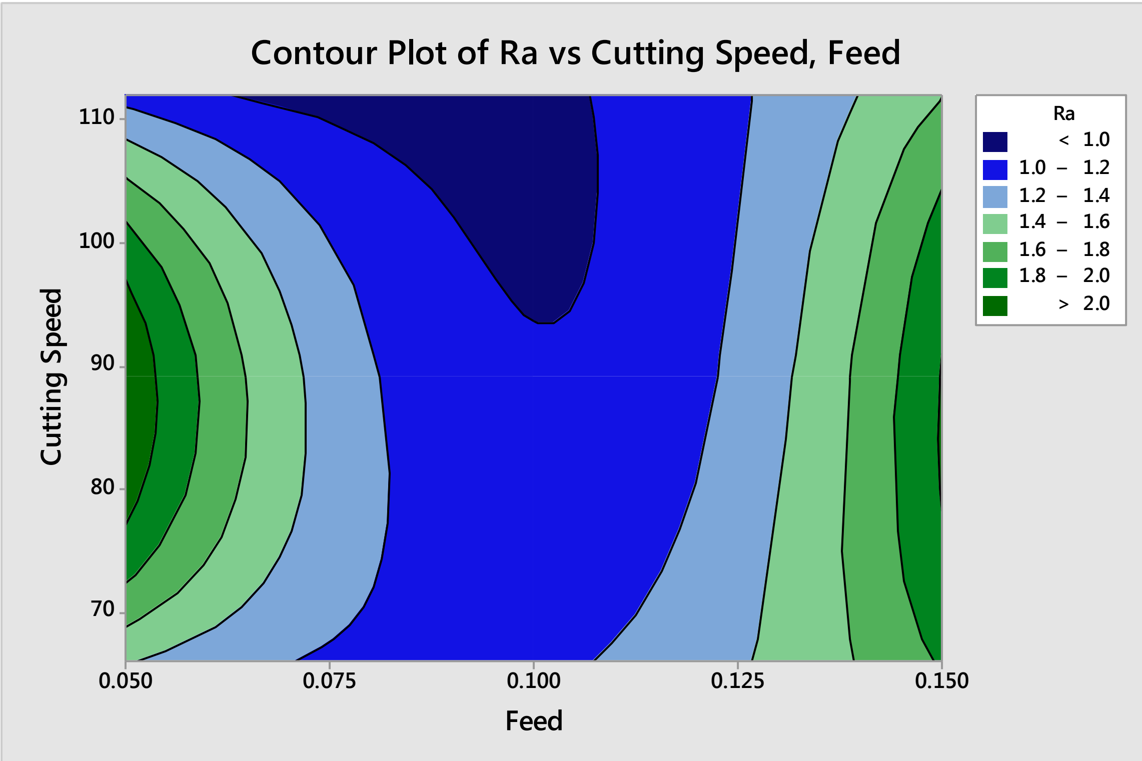


Fig 27: Contour plot of Ra vs Cutting Speed, Feed

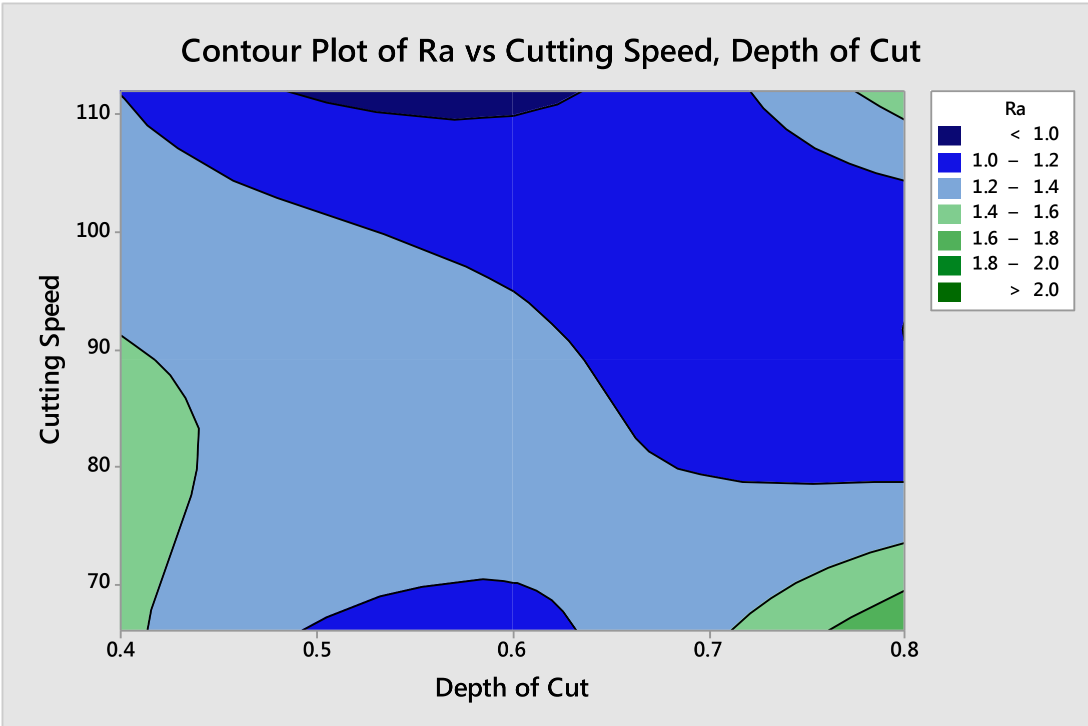


Fig 28: Contour plot of Ra vs Cutting Speed, Depth of Cut

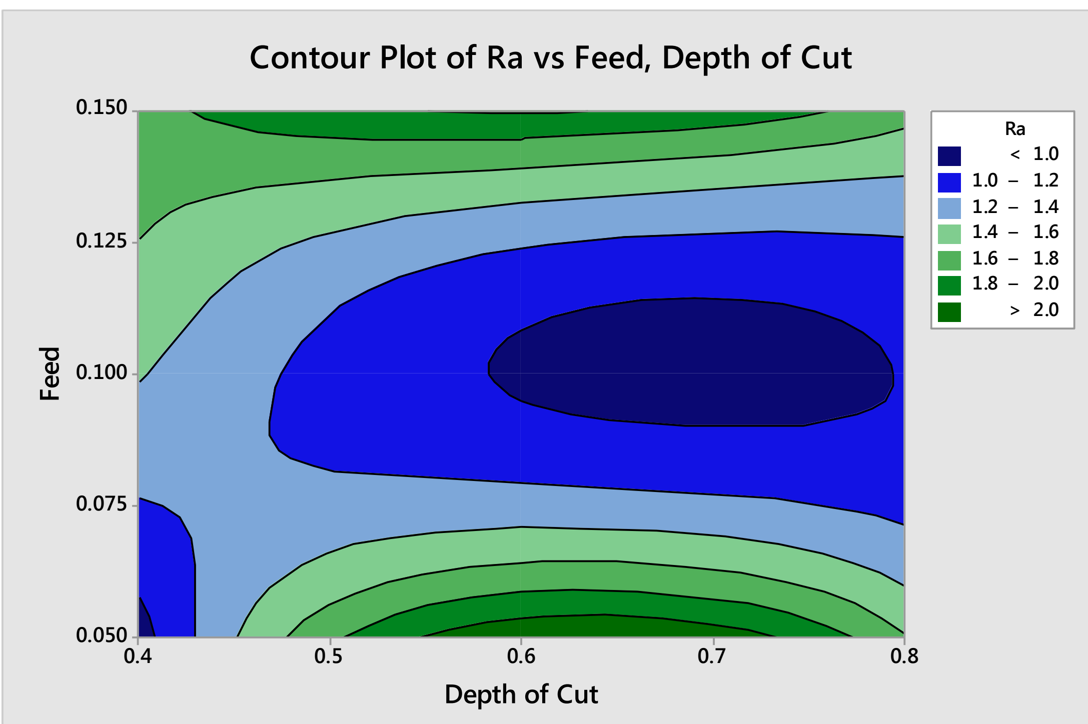


Fig29:Contour plot of Ra vs Feed, Depth of Cut

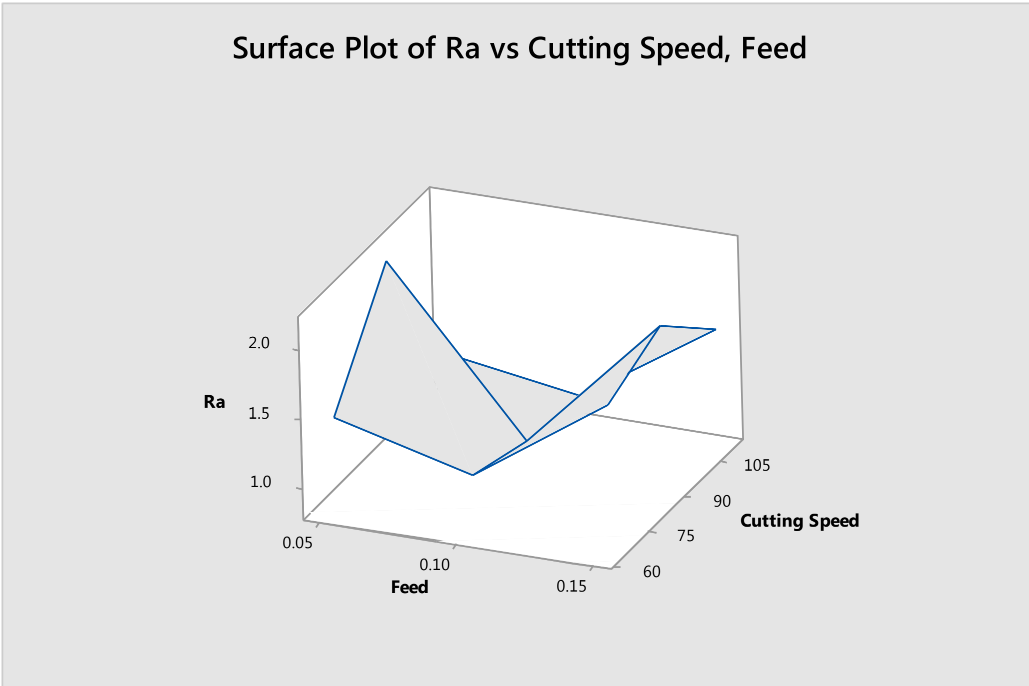


Fig 30: Surface plot of Ra vs Cutting Speed, Feed

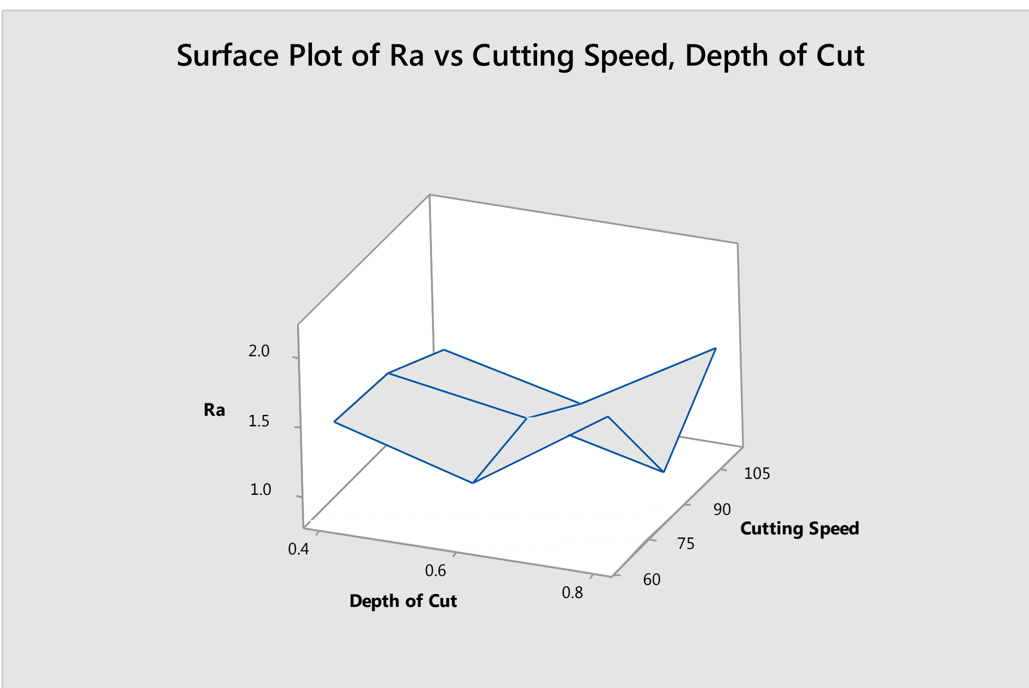


Fig 31: Surface plot of Ra vs Cutting Speed, Depth of cut

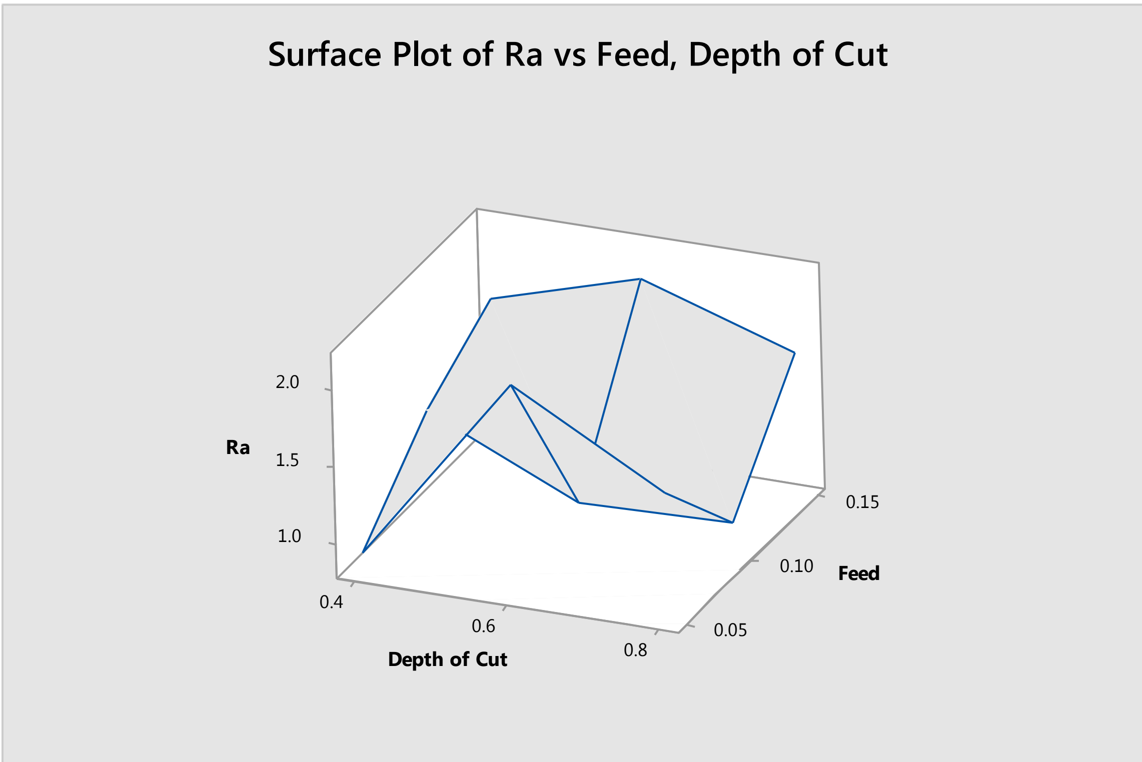


Fig 32: Surface plot of Ra vs Feed, Depth of cut

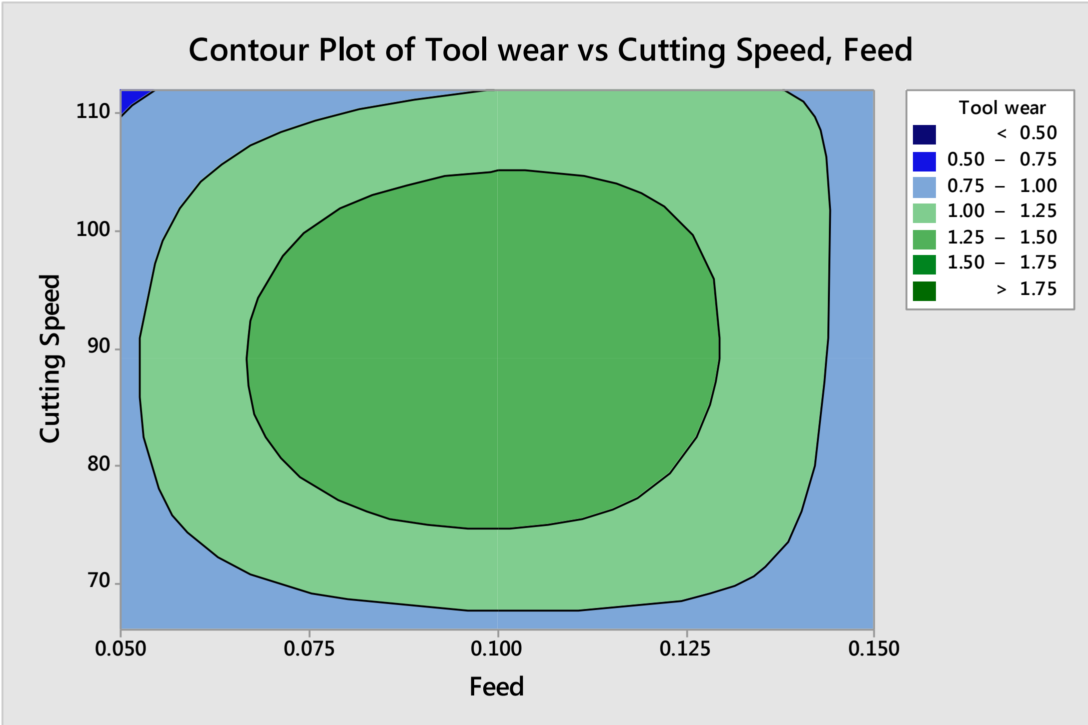


Fig 33: Contour plot of Tool Wear vs Cutting Speed, Feed

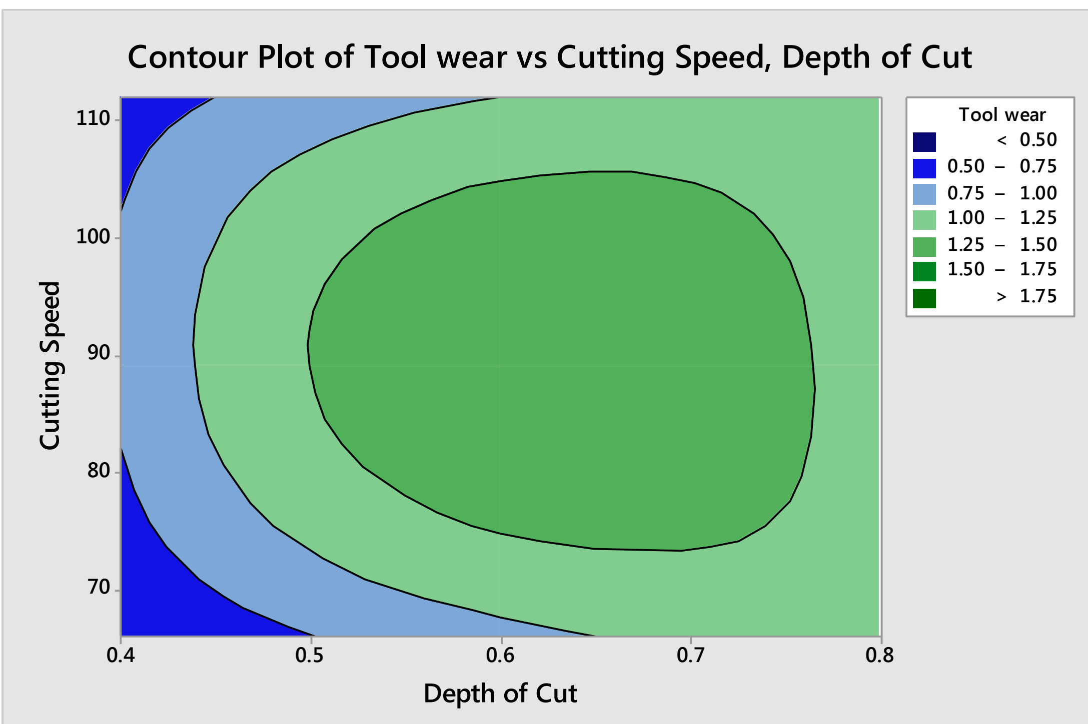


Fig34:Contour plot of Tool Wear vs Cutting Speed, Depth of Cut

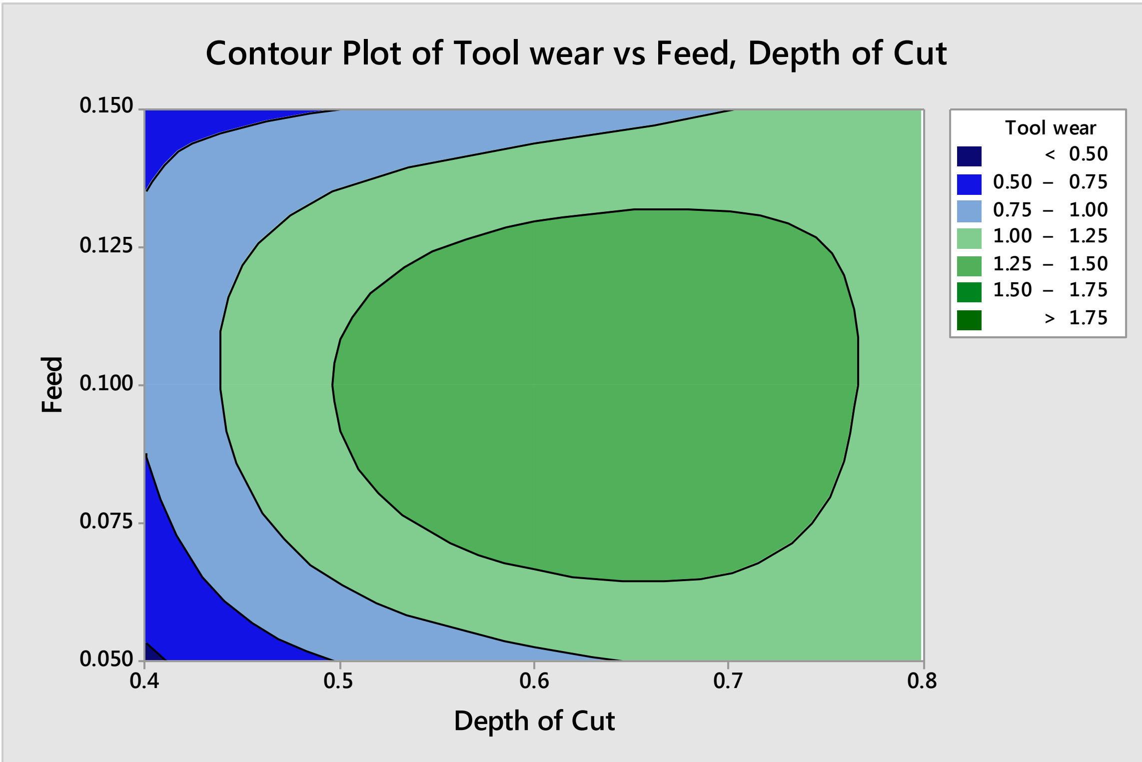


Fig 35: Contour plot of Tool Wear vs Feed, Depth of Cut

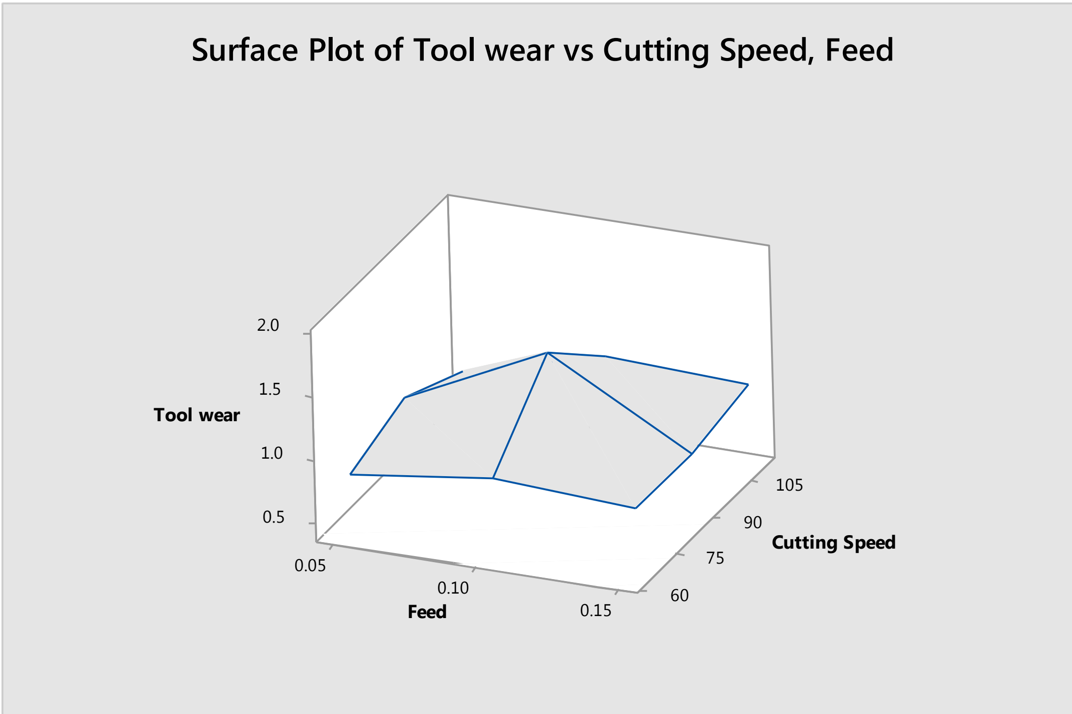


Fig 36: Surface plot of Tool Wear vs Cutting Speed, Feed

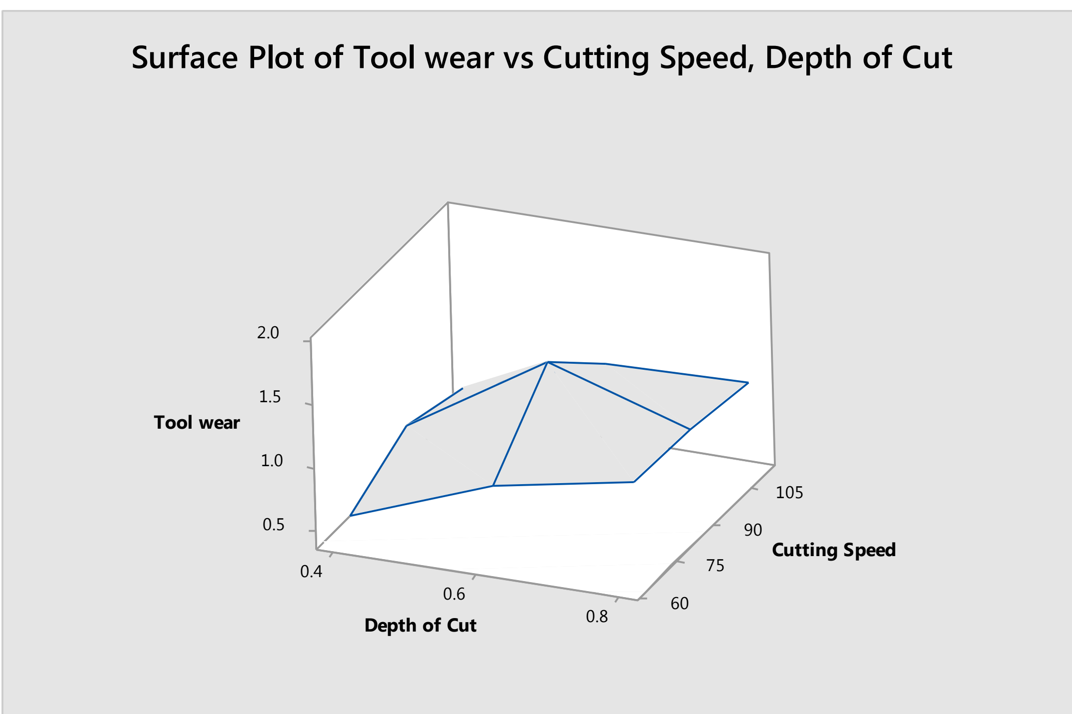


Fig 37: Surface plot of Tool Wear vs Cutting Speed, Depth of Cut

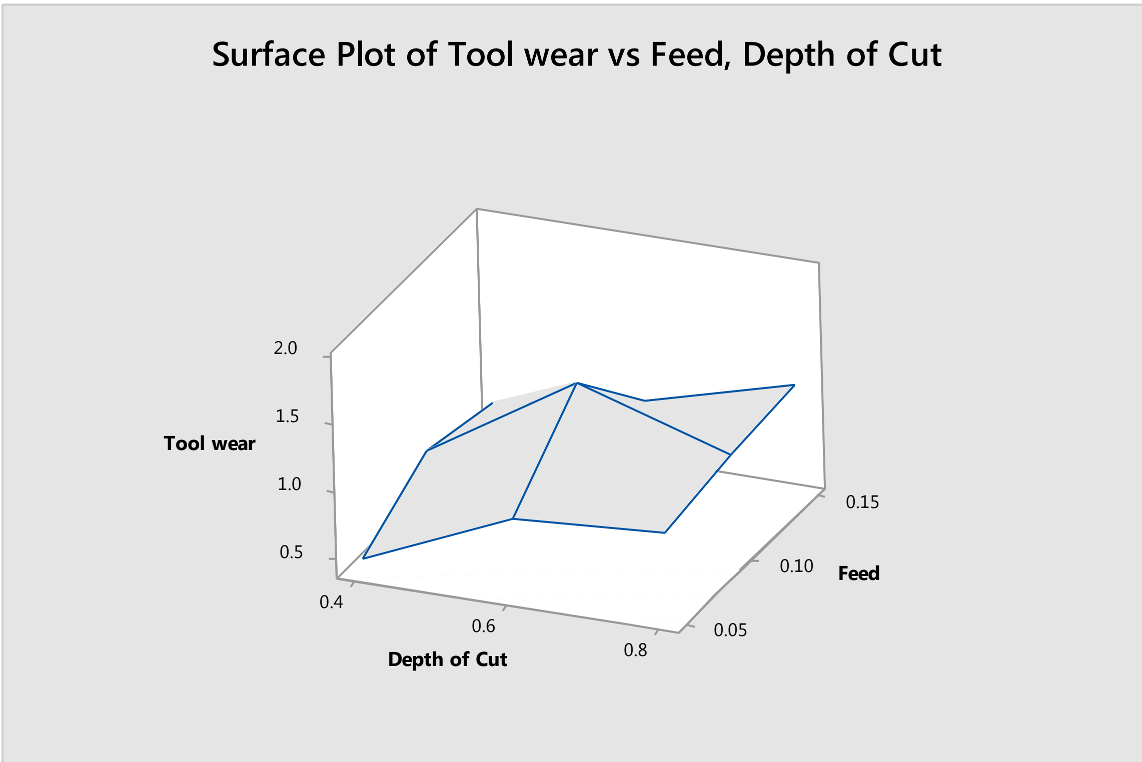


Fig 38: Surface plot of Tool Wear vs Feed, Depth of Cut

4.2.4 OPTIMUM SETTINGS

The three best optimal settings are shown in Table 12 below. The best setting is found to be

V_c = 112 m/min, f = 0.0540404 mm/rev and d = 0.4 mm

Table 12: Top three optimum settings

Solution	Cutting Speed	Feed	Depth of Cut	Tool wear Fit	Ra Fit	Composite desirability
1	112	0.0540404	0.4	0.518828	0.869883	0.968857
2	66	0.0723647	0.410652	0.654968	0.860066	0.921227
3	66	0.062364	0.4	0.53775	0.977706	0.920842

The optimization plot is shown in Fig 39. It shows how the desired response (surface roughness and tool wear) varies with increase in cutting speed, feed and depth of cut). The values that maximize the desirability give the optimal setting.

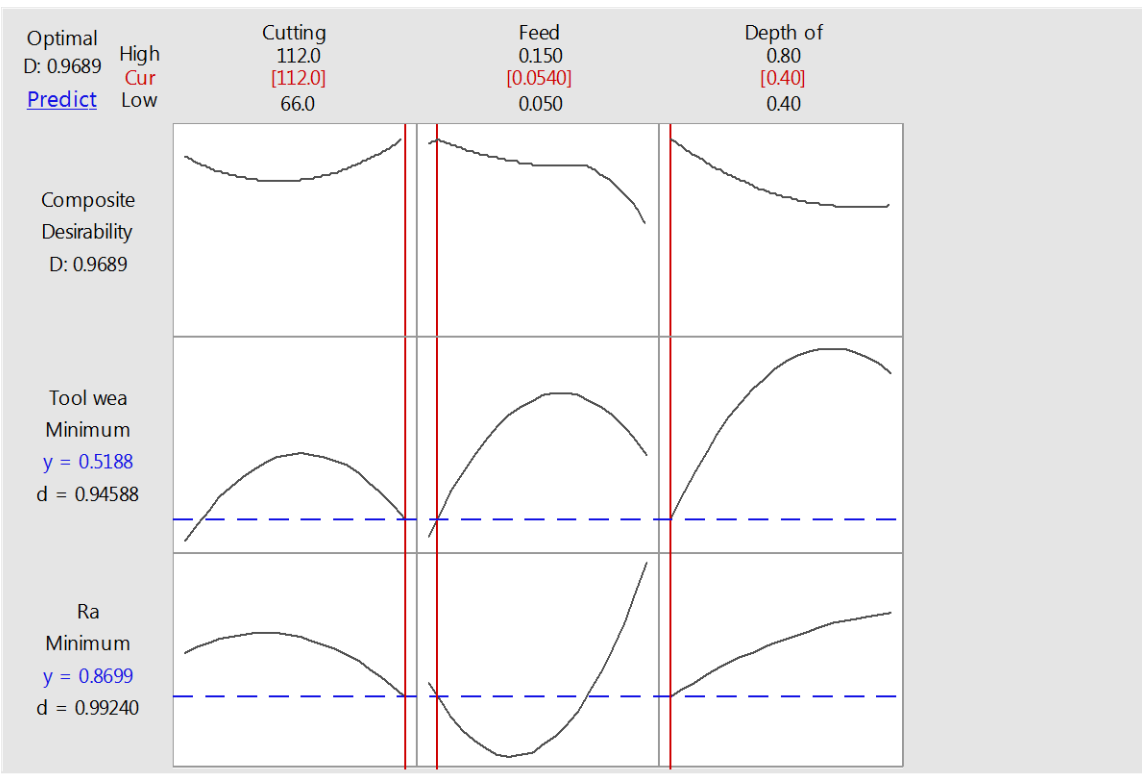


Fig 39: Optimization plot

Chapter 6 CONCLUSIONS

6.1 CONCLUSIONS

RSM was successfully applied in optimizing the surface roughness and tool wear for the chosen tool-work combination and for the selected domain of the input machining parameters. ANOVA analysis was carried out and it is observed that feed is the most significant factor affecting the surface roughness, closely followed by cutting speed and depth of cut, while the only significant factor affecting the tool wear was found to be the depth of cut. The optimum running condition was found to be at V_c (112 m/min), f (0.0540404 mm/rev) and d (0.4 mm). Empirical models for surface roughness and tool wear have been determined based on which predictions can be carried out for output responses for appropriate applications.

6.2 SCOPE FOR FUTURE STUDY

The experiment was originally planned to be conducted with the involvement of mist application of cutting fluid. Due to unavailability of the mist application device due to some constraints, the experiment was conducted in a dry cutting environment. Mist application of cutting fluid could be applied in the future to the same tool-work combination for the same domain of cutting parameters as chosen in the present study and its effects on the surface roughness and tool wear could be studied and analysed.

Another improvement that can be made to the present study is that cutting forces could be added as an output response in addition to surface roughness and tool wear. An attempt can then be made to find out optimum machining parameters so that multiple variables can be optimized via a single experimental trial.

Furthermore, any tool geometry parameter from among nose its effects on the output responses and in order to increase the effectiveness of the fitted model.

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